Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Transformation Optics and Experiments

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Abstract

The rapid development of artificial metamaterials have provided many opportunities for new device design, but brought the need for tools that can provide us an efficient design for a special functionality. In 2006, Pendry et al. proposed the technique of transformation optics (TO), which fulfilled the requirement for such a tool. For TO devices, the composing material implements a coordinate transformation for EM fields, and the electric permittivity and magnetic permeability of the material could be derived from the methodology of TO. Transformation electromagnetic or transformation optics provides a freedom way to control the electric currents and potentials. Transformation optics/electromagnetics has been used to design and create a lot of novel devices theoretically and numerically. We have designed and fabricated a series of transformation devices, such as kinds of carpet cloaks, flattened Luneburg lens and illusion devices, etc. The measurement results agree exceptionally well with theoretical predictions and simulation results, showing perfect performance. Manipulation of electromagnetic fields with the control of anisotropic conductivities has a lot of potential applications, such as high-efficient wireless communications, camouflage and military hiding.

Keywords: Transformation Optics, Experiments.

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6. W. X. Jiang, T. J. Cui, X. M. Yang, Q. Cheng, R. Liu, and D. R. Smith, “Invisibility cloak without singularity,” *Appl. Phys. Lett.*, Vol. 93, 194102, 2008.

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10. W. X. Jiang, T. J. Cui, X. M. Yang, H. F. Ma, and Q. Cheng, "Shrinking an arbitrary object as one desires using metamaterials," *Applied Physics Letters*, vol. 98, 204101, May 2011.
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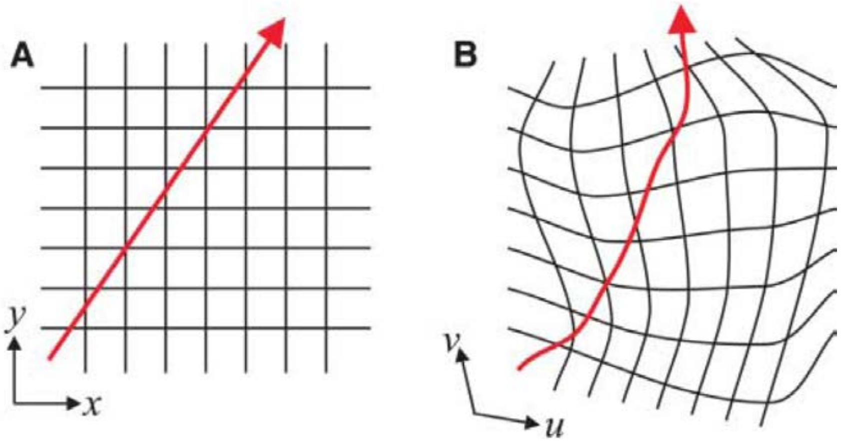
Outline

- ◆ Background and motivation
- ◆ Previous theoretical work on TO
- ◆ 2D and 3D Carpet cloaks
- ◆ Illusion devices
- ◆ EM black hole
- ◆ Flattened Luneburg lens
- ◆ High-resolution imaging lens
- ◆ Summary

Transformation Optics

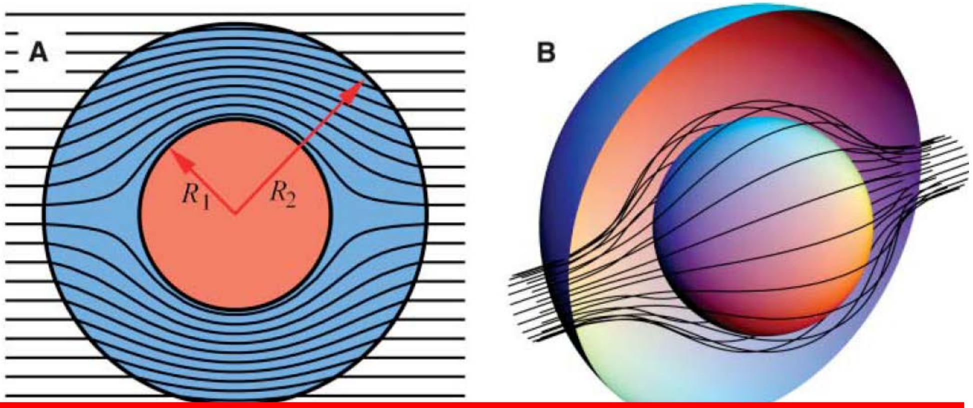


$$\varepsilon'_u = \varepsilon_u \frac{Q_u Q_v Q_w}{Q_u^2},$$

$$\mu'_u = \mu_u \frac{Q_u Q_v Q_w}{Q_u^2}, \text{ etc.}$$

Pendry, *Science* **312,** 1780 (2006); Leonhardt, *Science* **312,** 1777 (2006)

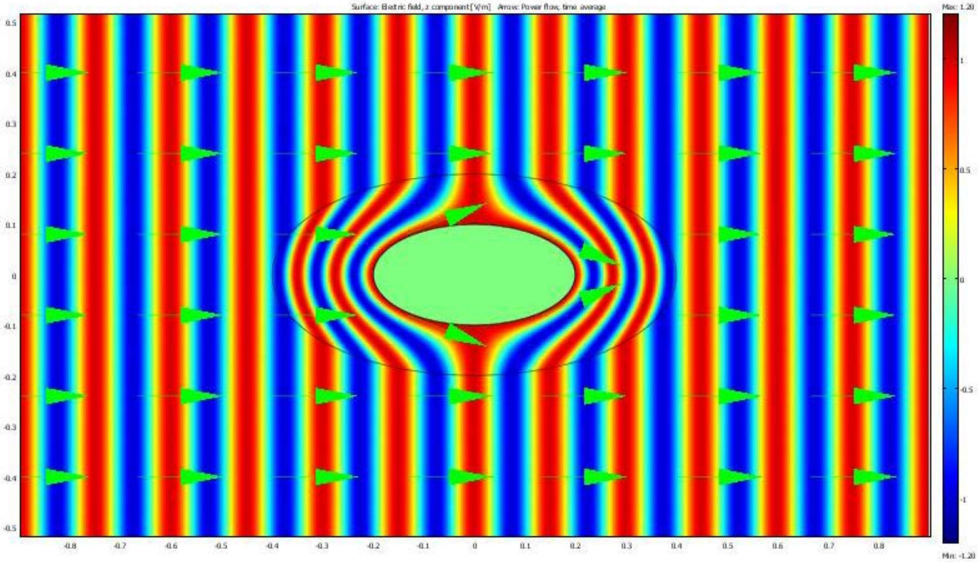
- Elegant
- General and powerful
- Accurate



Our Motivation:

- Microwave
- New Experiments
- New Applications

Elliptical Cloaks



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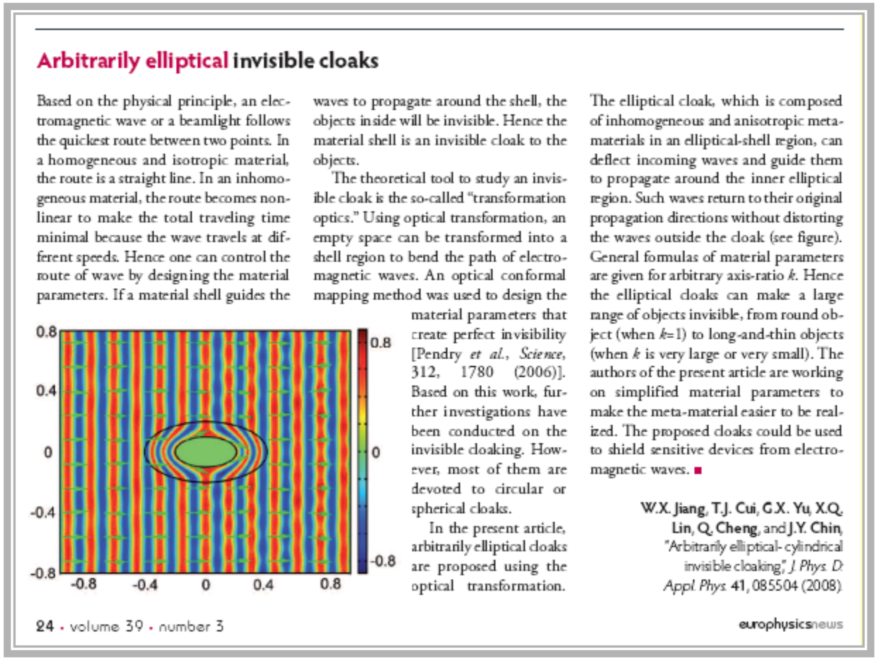

Arbitrarily elliptical invisible cloaks

Based on the physical principle, an electromagnetic wave or a beamlight follows the quickest route between two points. In a homogeneous and isotropic material, the route is a straight line. In an inhomogeneous material, the route becomes nonlinear to make the total traveling time minimal because the wave travels at different speeds. Hence one can control the route of wave by designing the material parameters. If a material shell guides the waves to propagate around the shell, the objects inside will be invisible. Hence the material shell is an invisible cloak to the objects.

The theoretical tool to study an invisible cloak is the so-called "transformation optics." Using optical transformation, an empty space can be transformed into a shell region to bend the path of electromagnetic waves. An optical conformal mapping method was used to design the material parameters that create perfect invisibility [Pendry *et al.*, *Science*, 312, 1780 (2006)]. Based on this work, further investigations have been conducted on the invisible cloaking. However, most of them are devoted to circular or spherical cloaks.

In the present article, arbitrarily elliptical cloaks are proposed using the optical transformation. The elliptical cloak, which is composed of inhomogeneous and anisotropic metamaterials in an elliptical-shell region, can deflect incoming waves and guide them to propagate around the inner elliptical region. Such waves return to their original propagation directions without distorting the waves outside the cloak (see figure). General formulas of material parameters are given for arbitrary axis-ratio *k*. Hence the elliptical cloaks can make a large range of objects invisible, from round object (when *k*=1) to long-and-thin objects (when *k* is very large or very small). The authors of the present article are working on simplified material parameters to make the meta-material easier to be realized. The proposed cloaks could be used to shield sensitive devices from electromagnetic waves. ■

W.X. Jiang, T.J. Cui, G.X. Yu, X.Q. Lin, Q. Cheng, and **J.Y. Chin,** "Arbitrarily elliptical-cylindrical invisible cloaking," *J. Phys. D: Appl. Phys.* 41, 085504 (2008).

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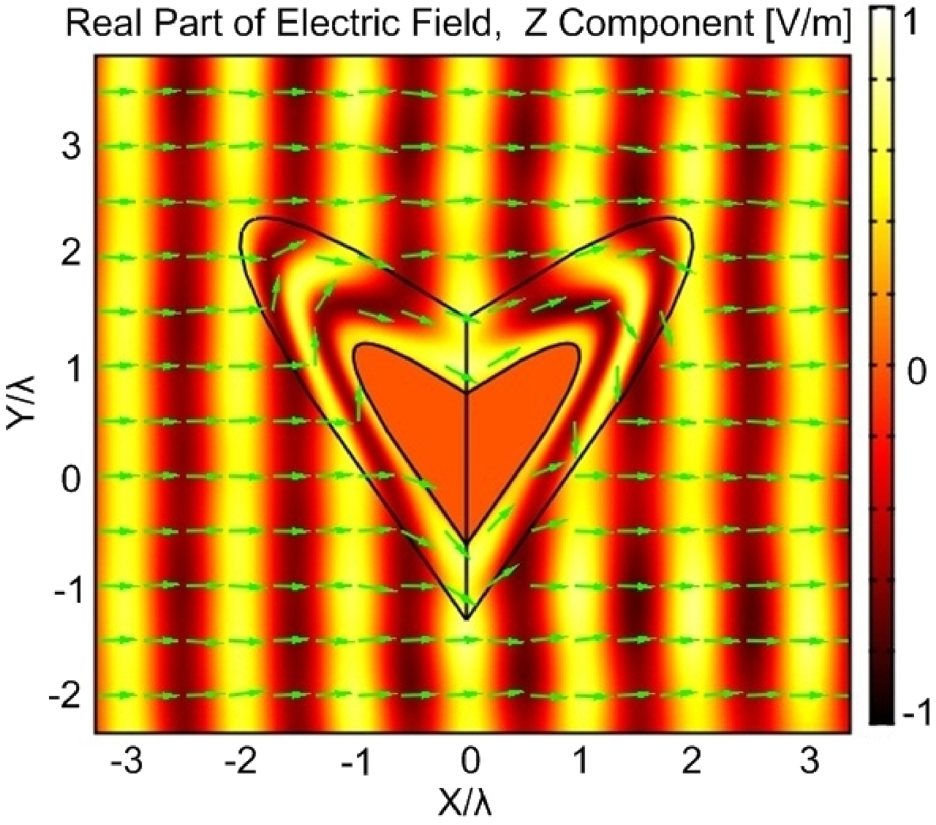
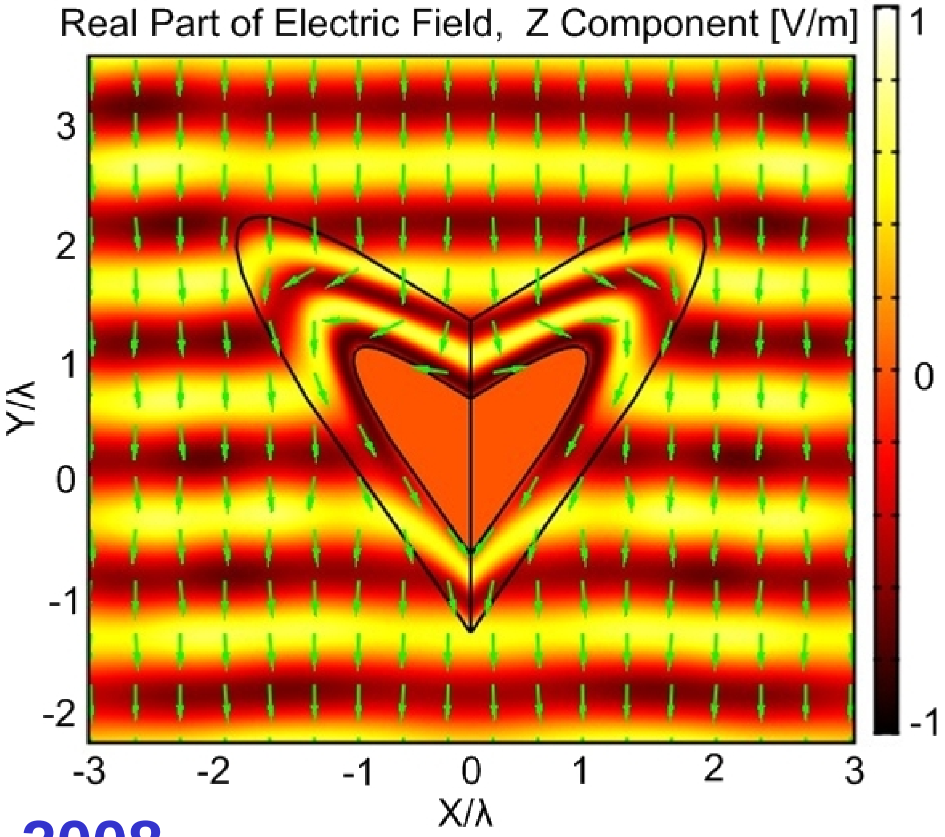
Elliptical Invisible Cloaks

J. Phys. D: Appl. Phys., 41, 085504 (2008)

highly cited paper

Arbitrarily-Shaped Cloaks

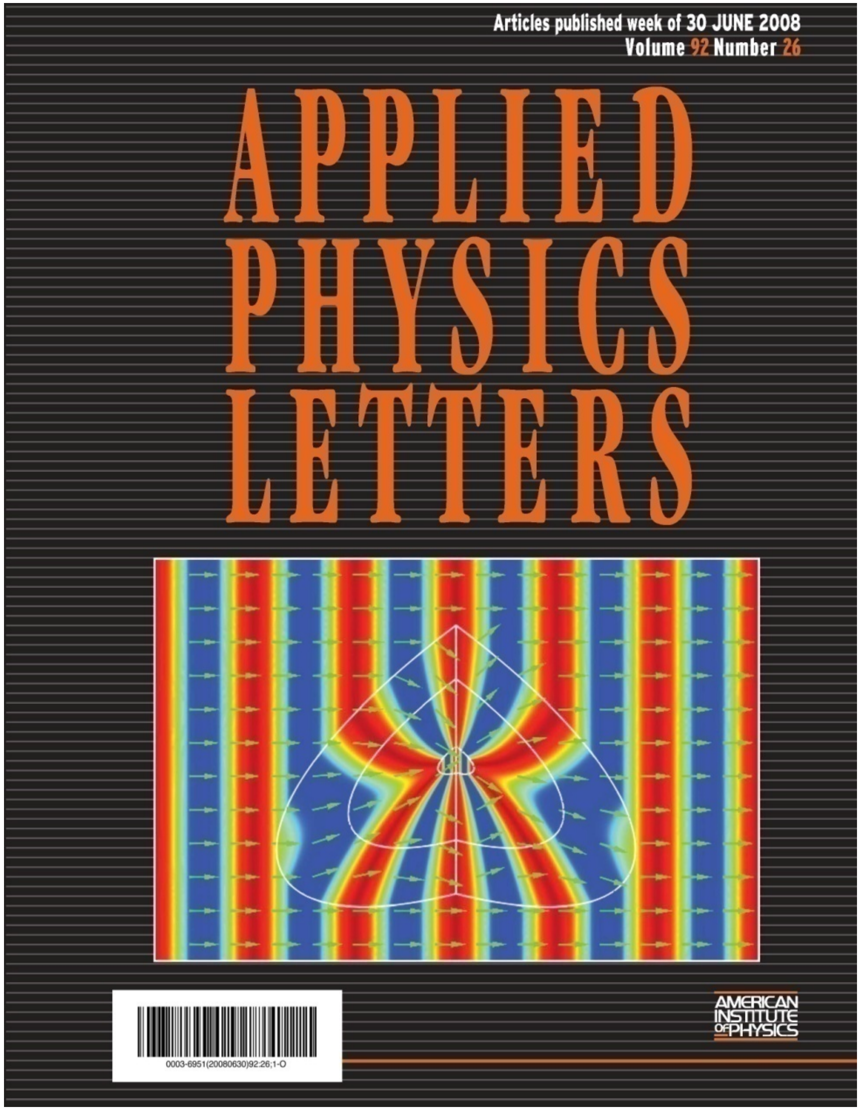




***Physical Review E*, 77, 066607, 2008**

highly cited paper

Arbitrarily-Shaped Concentrator



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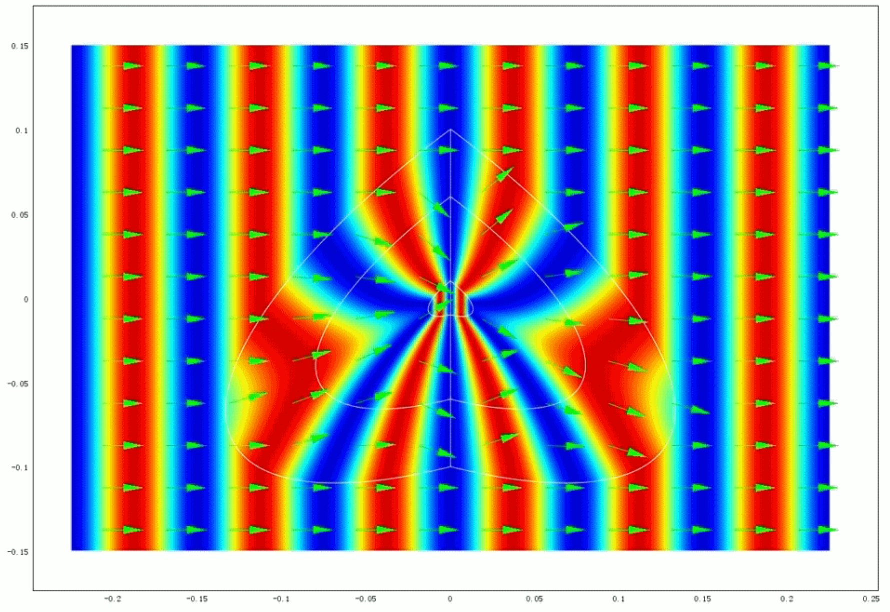
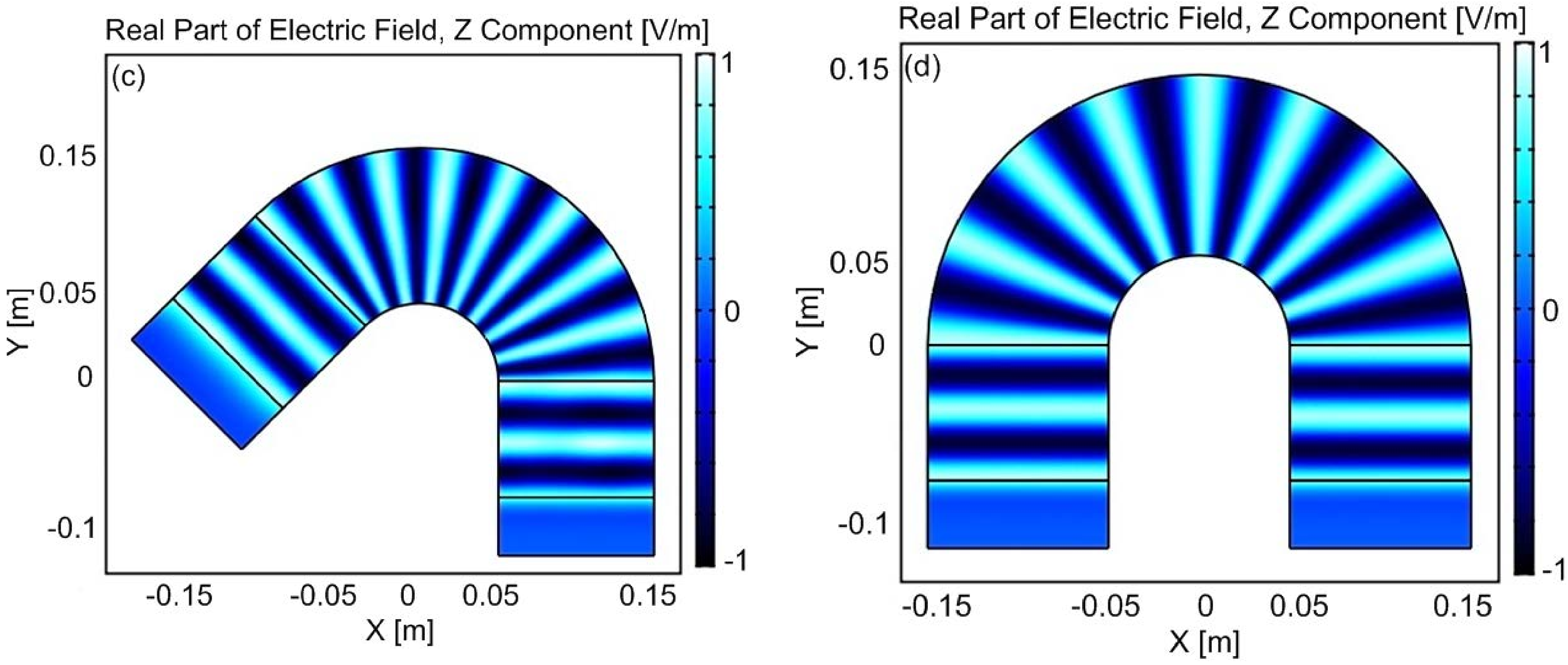


The rectangular concentrator can be easily used in amplifying plane waves.

Appl. Phys. Lett., 92, 264101 (2008)

highly cited paper

Wave Bending

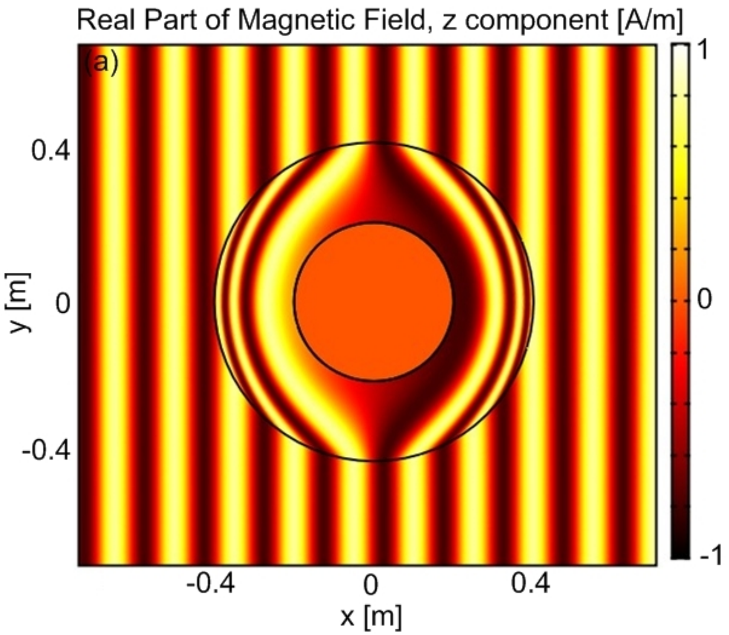


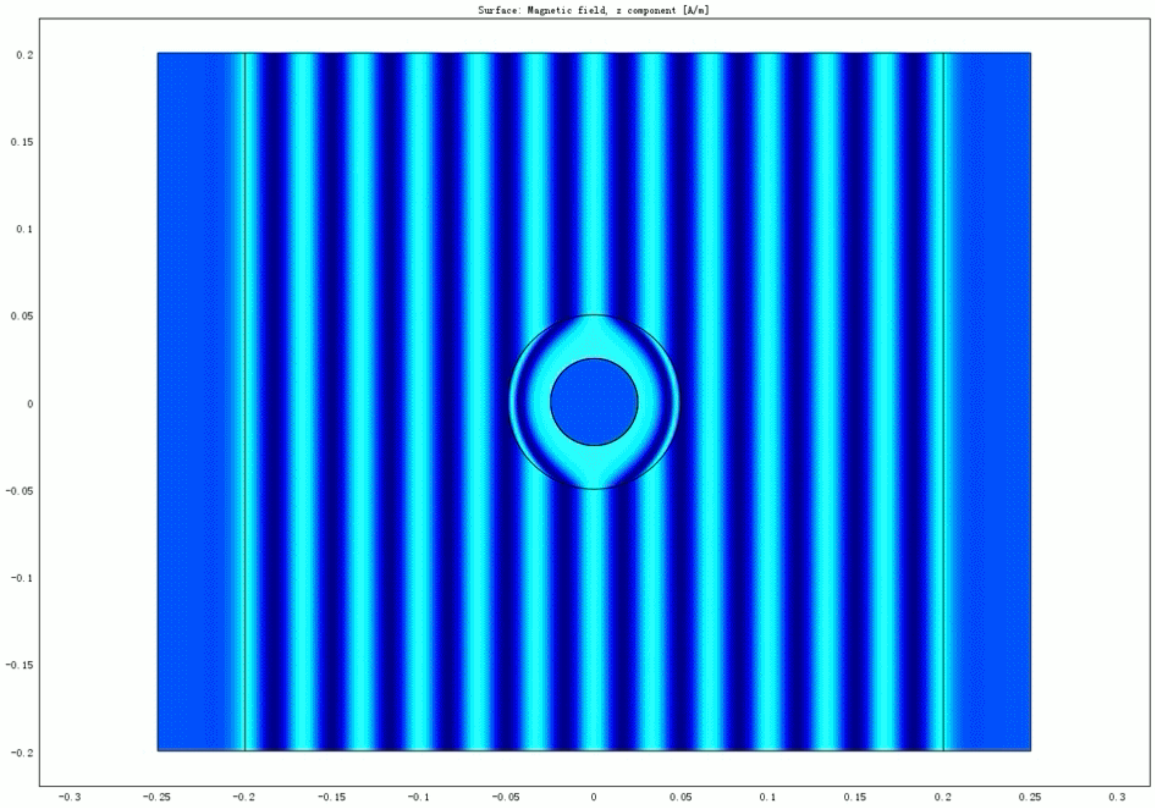
$$\mu_z = 1, \varepsilon_r = h^2 / (\theta r)^2, \varepsilon_\phi = 1$$

***Physical Review E*, 78, 066607, 2008**

Cloak Without Singularity

- **When the becomes small, an approximate circular cloak is obtained.**

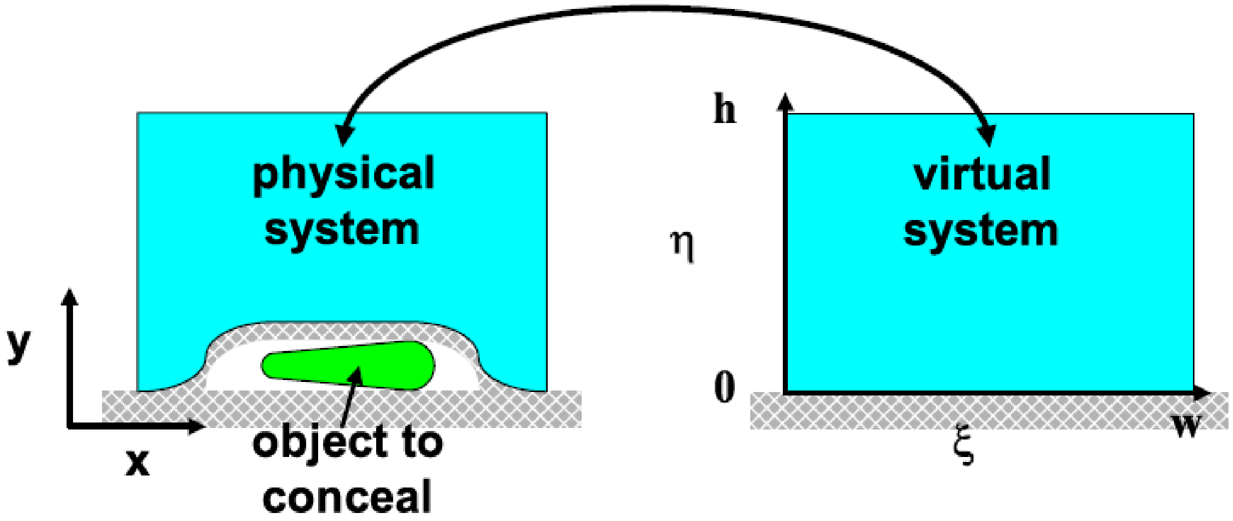




***Appl. Phys. Lett.*, 93, 194102, 2008**

Carpet Cloak

- **Carpet cloaking takes advantage of transformation optics from a line (or a plane in 3D case). The object can be hided on the ground by covering designed metamaterials on the top, shown in the figure.**


physical system
virtual system
object to conceal
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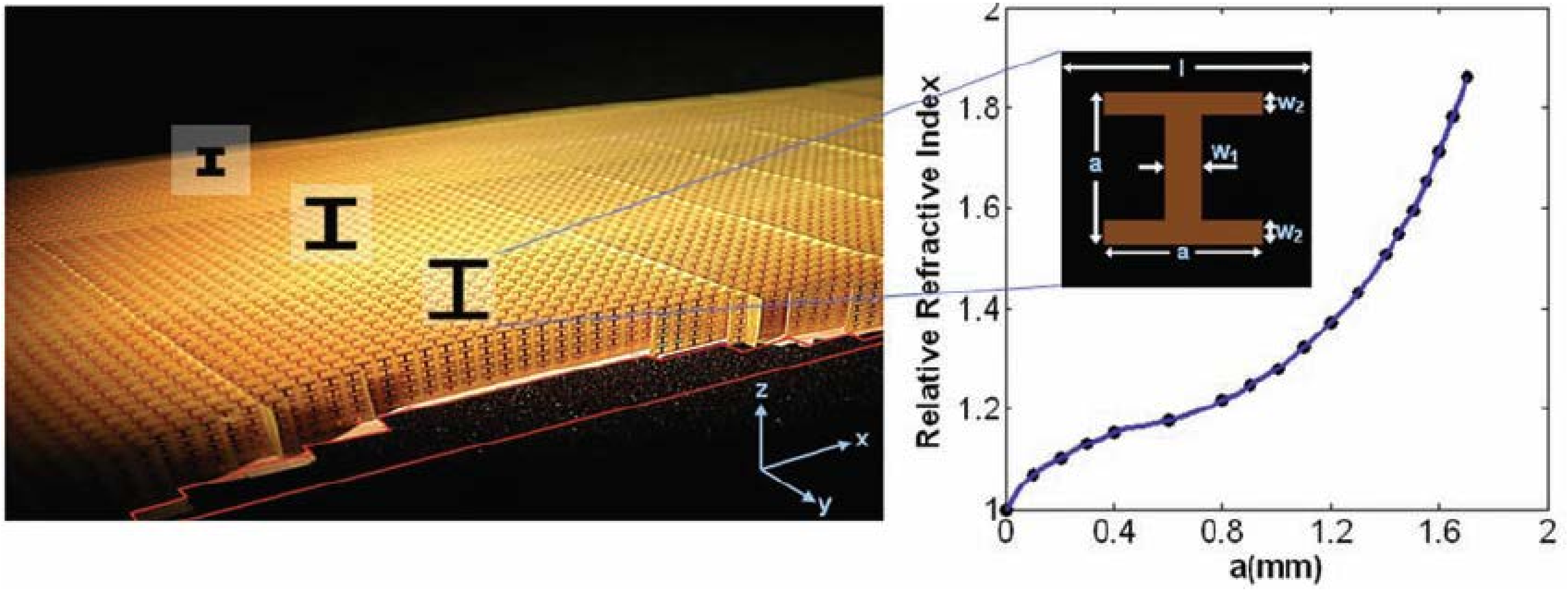
***Li and Pendry, Phys. Rev. Lett.* 101, 203901, 2008.**

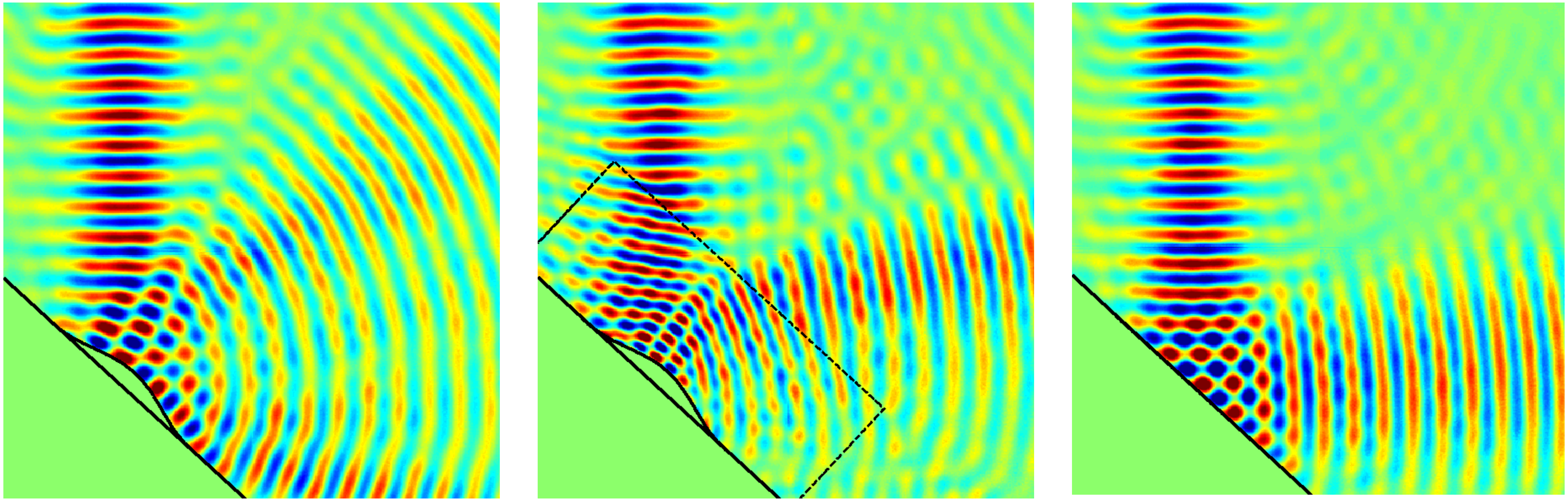
Carpet Cloak

- **Working with Smith's group, we presented an experimental realization of the carpet cloak that conceals a perturbation on a flat conducting plane, under which an object can be hidden.**

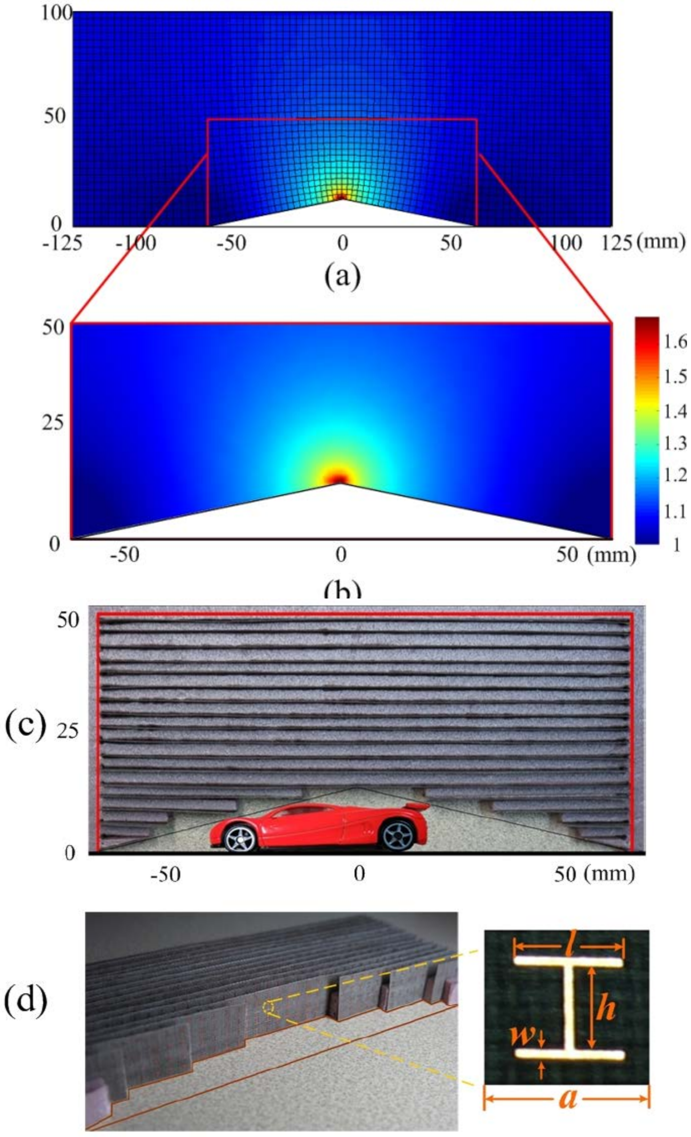


Liu, Ji, Mock, Chin, Cui*, Smith*, *Science* 323, 366 (2009)

Measurement Results



Compact-Size Carpet Cloak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1.5
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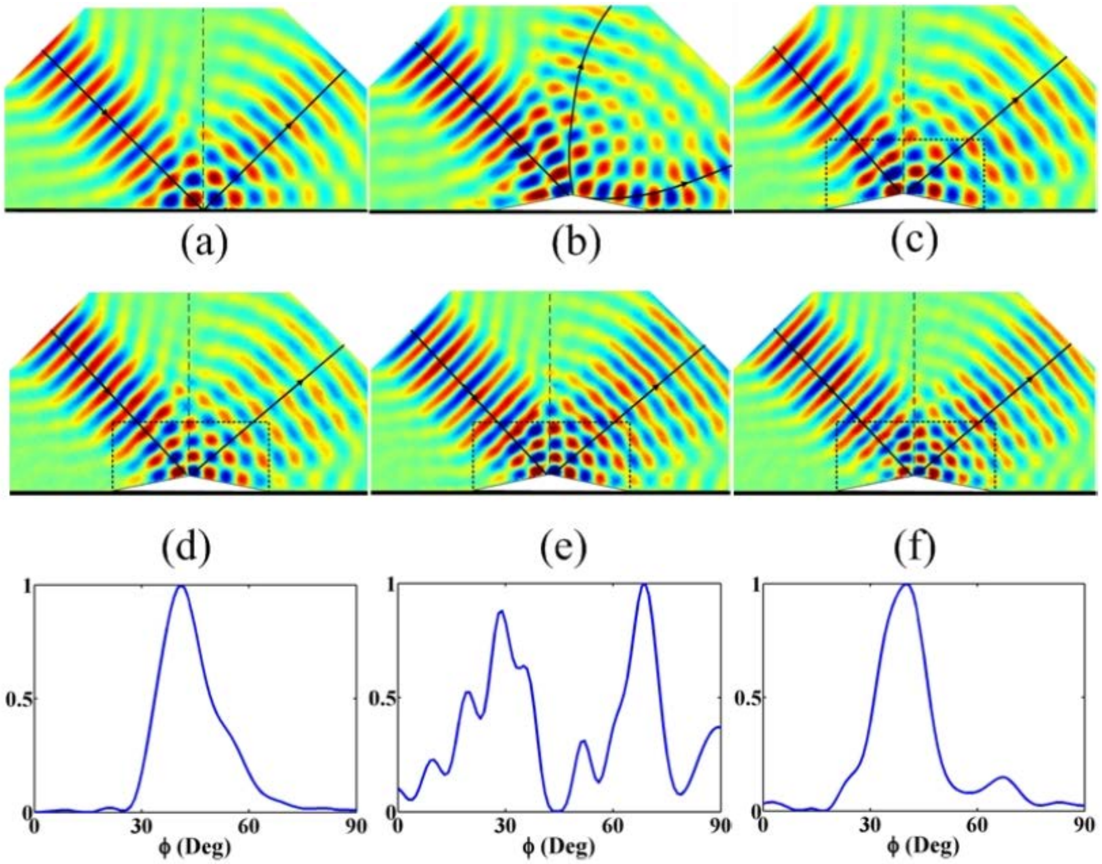
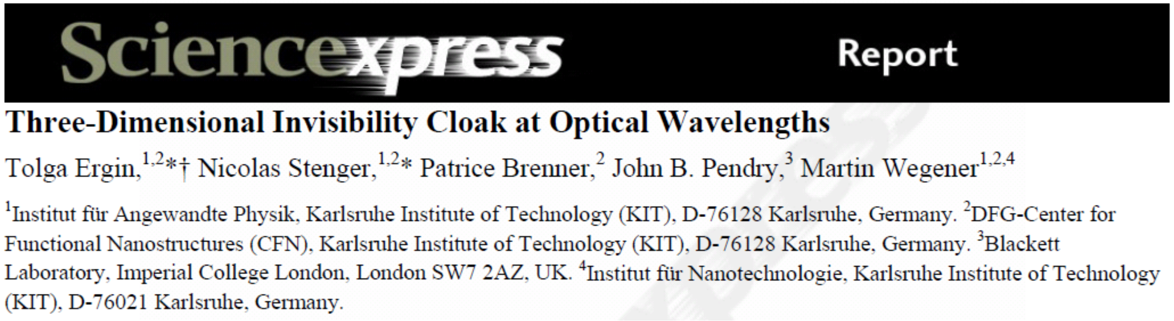


6 times smaller

Ma, Jiang, Cui, Opt. Exp. 17, p. 19947, 2009

3D Broadband Cloak

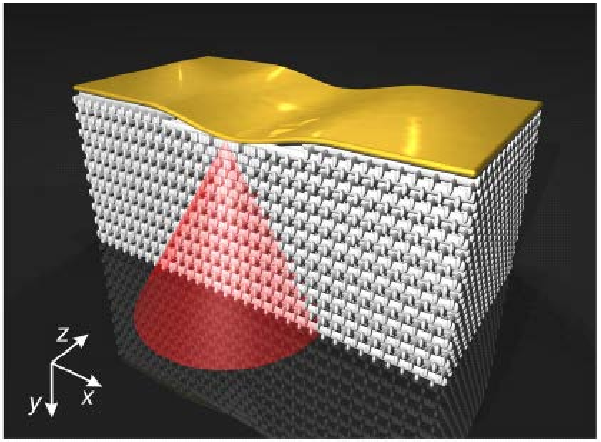


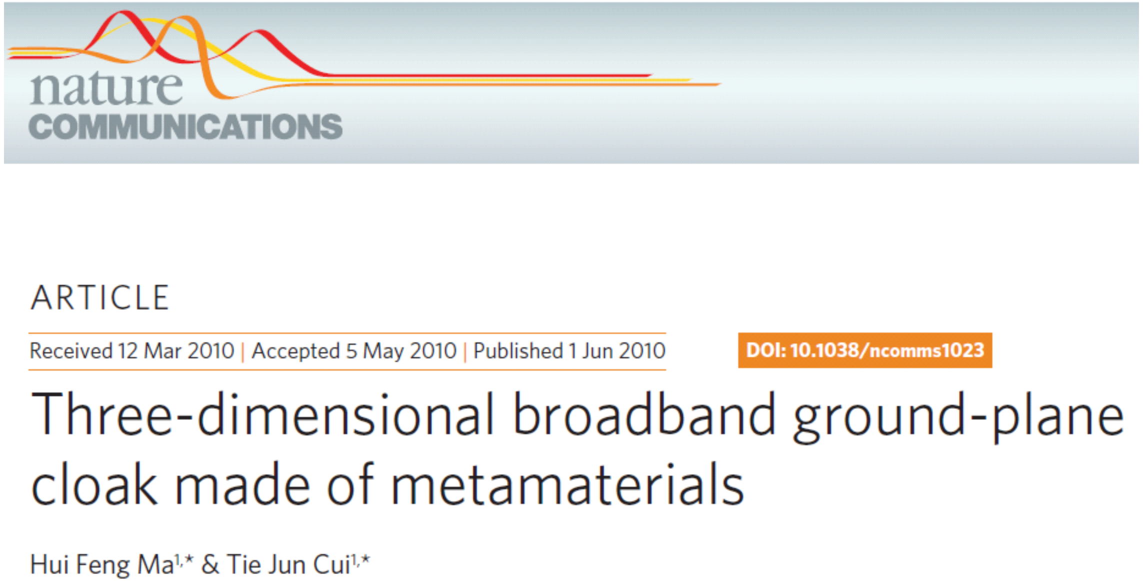
Sciencexpress Report

Three-Dimensional Invisibility Cloak at Optical Wavelengths

Tolga Ergin,[1,2]*† Nicolas Stenger,[1,2]* Patrice Brenner,[2] John B. Pendry,[3] Martin Wegener[1,2,4]

[1]Institut für Angewandte Physik, Karlsruhe Institute of Technology (KIT), D-76128 Karlsruhe, Germany. [2]DFG-Center for Functional Nanostructures (CFN), Karlsruhe Institute of Technology (KIT), D-76128 Karlsruhe, Germany. [3]Blackett Laboratory, Imperial College London, London SW7 2AZ, UK. [4]Institut für Nanotechnologie, Karlsruhe Institute of Technology (KIT), D-76021 Karlsruhe, Germany.





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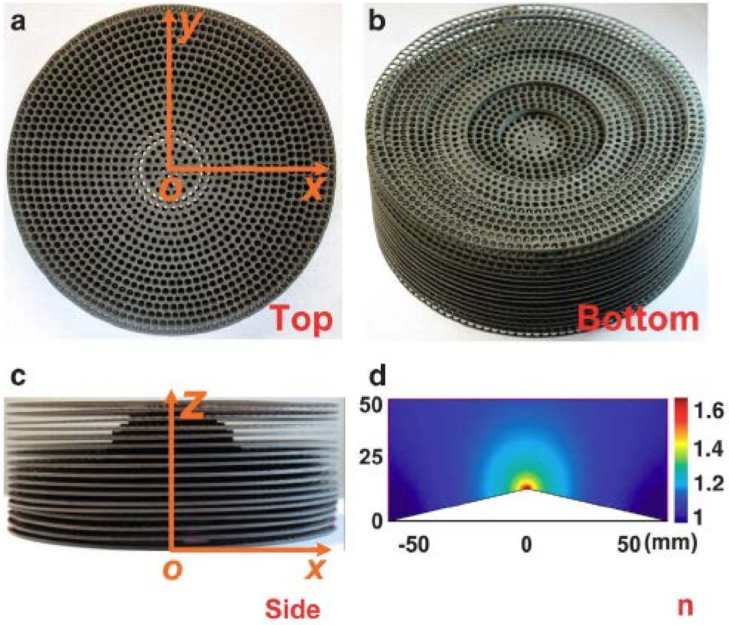
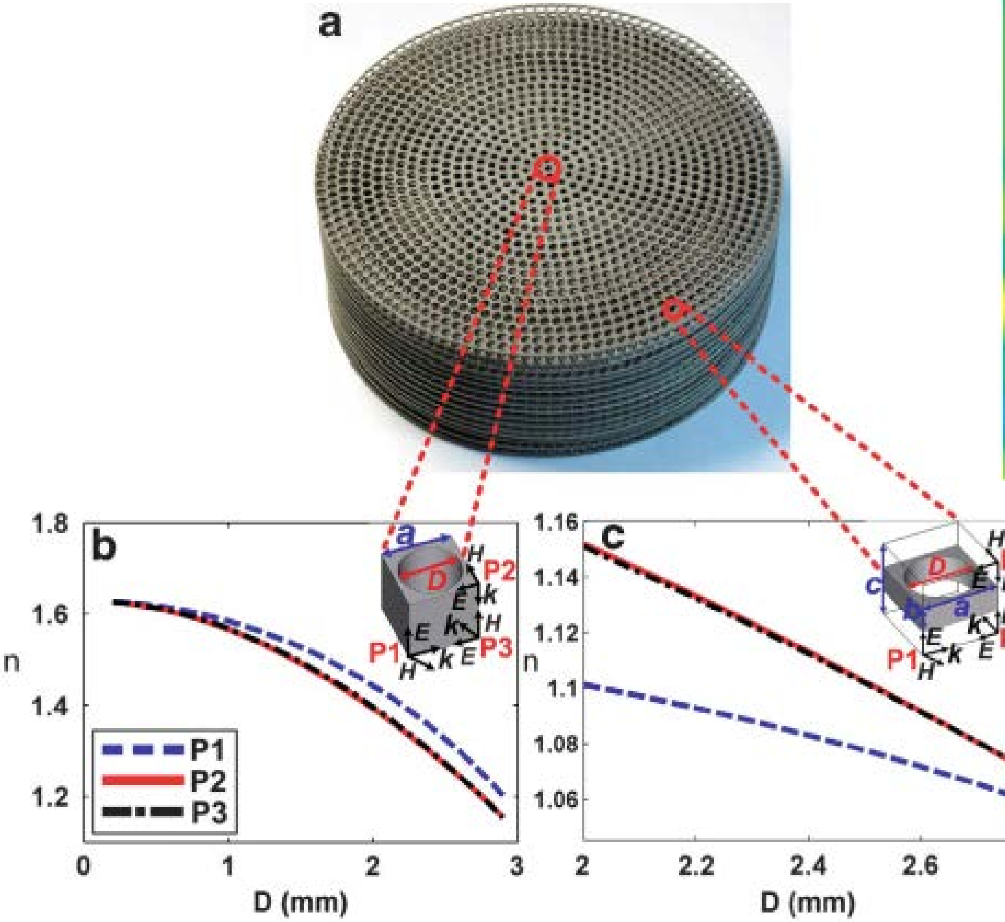
DOI: 10.1038/ncomms1023

Three-dimensional broadband ground-plane cloak made of metamaterials

Hui Feng Ma[1,*] & Tie Jun Cui[1,*]



H. F. Ma, T. J. Cui, Nat. Comm., 1, 21, June 2010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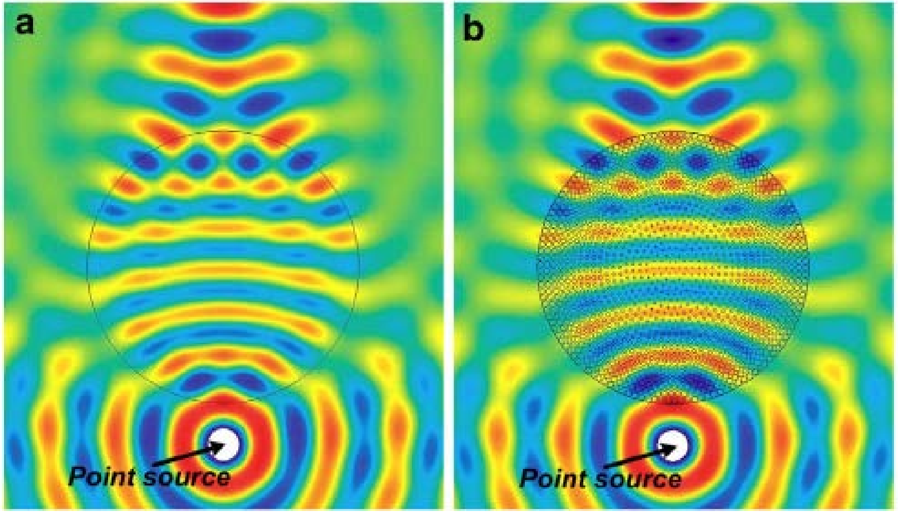
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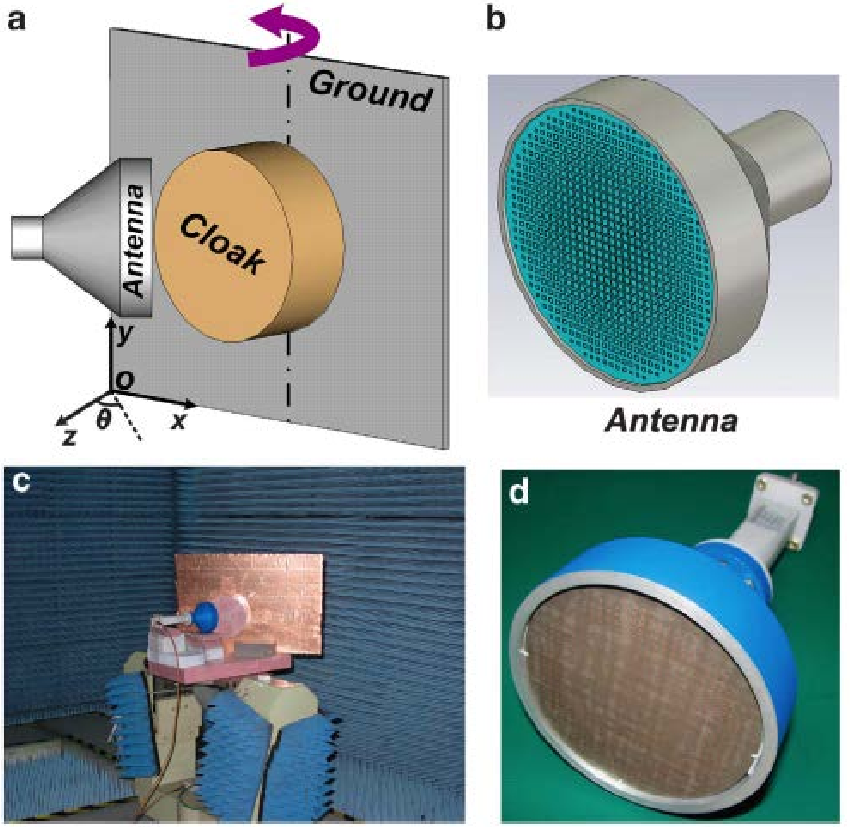
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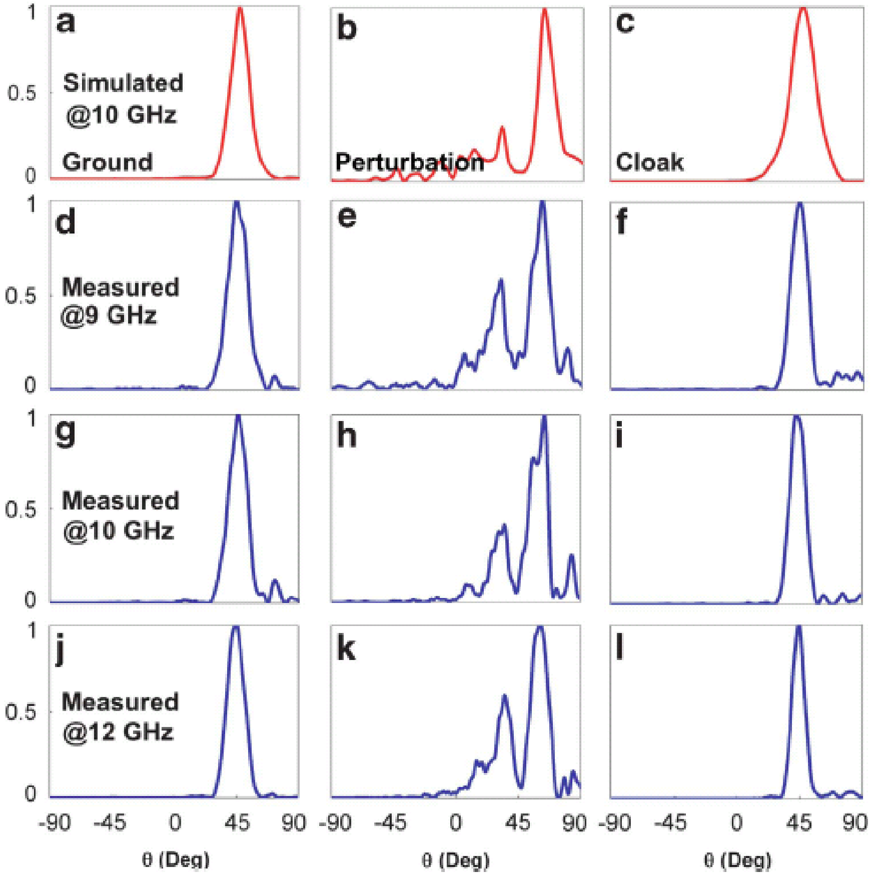

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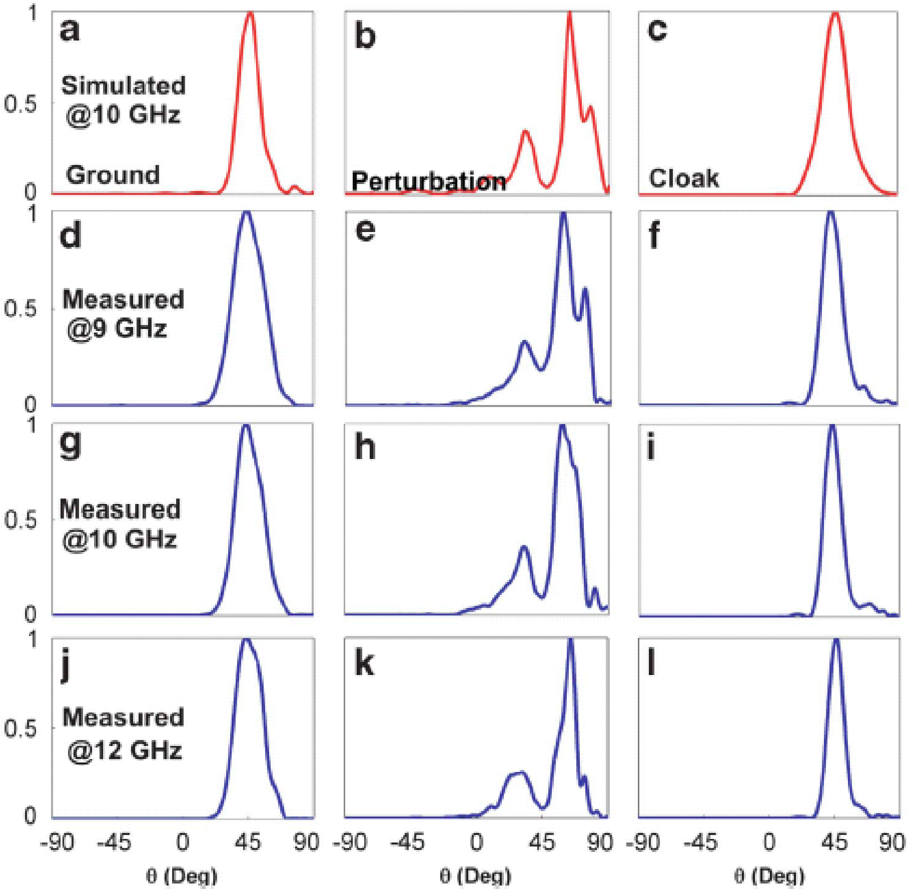
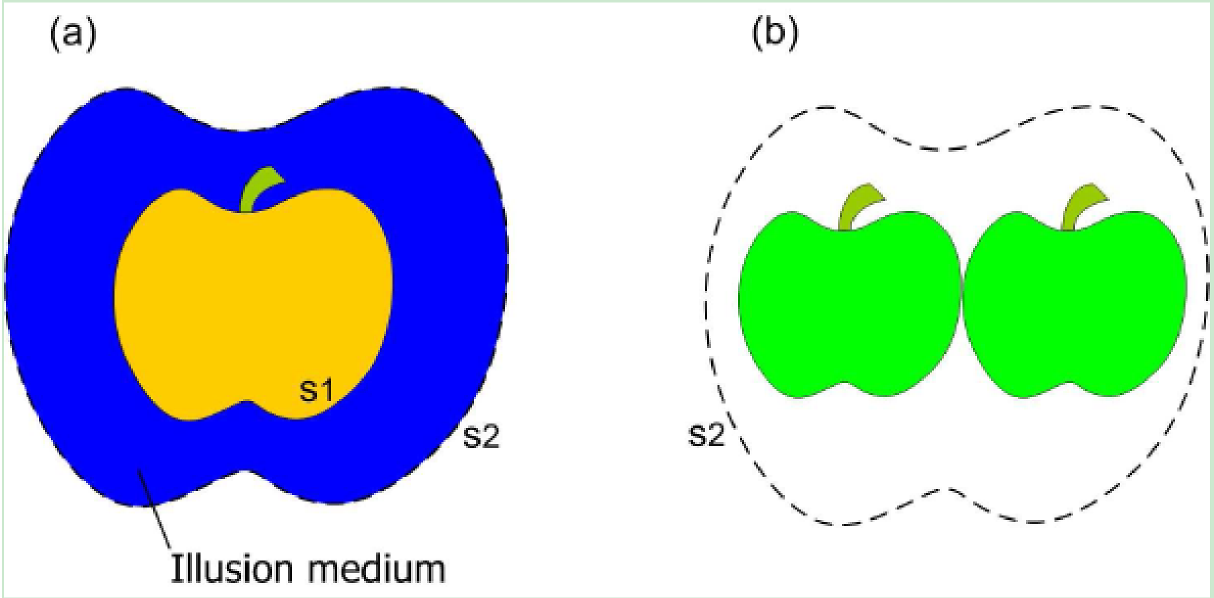


Horizontal Polarization

Illusion Media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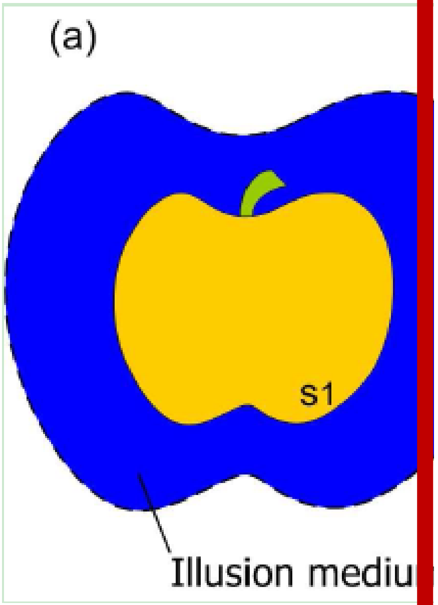
Illusion medium

- **We present an illusion medium layer which can make the enclosed actual object invisible and generate one or more virtual objects.**

W. X. Jiang, T. J. Cui, *et* al., APL, 96, 121910, 2010

Illu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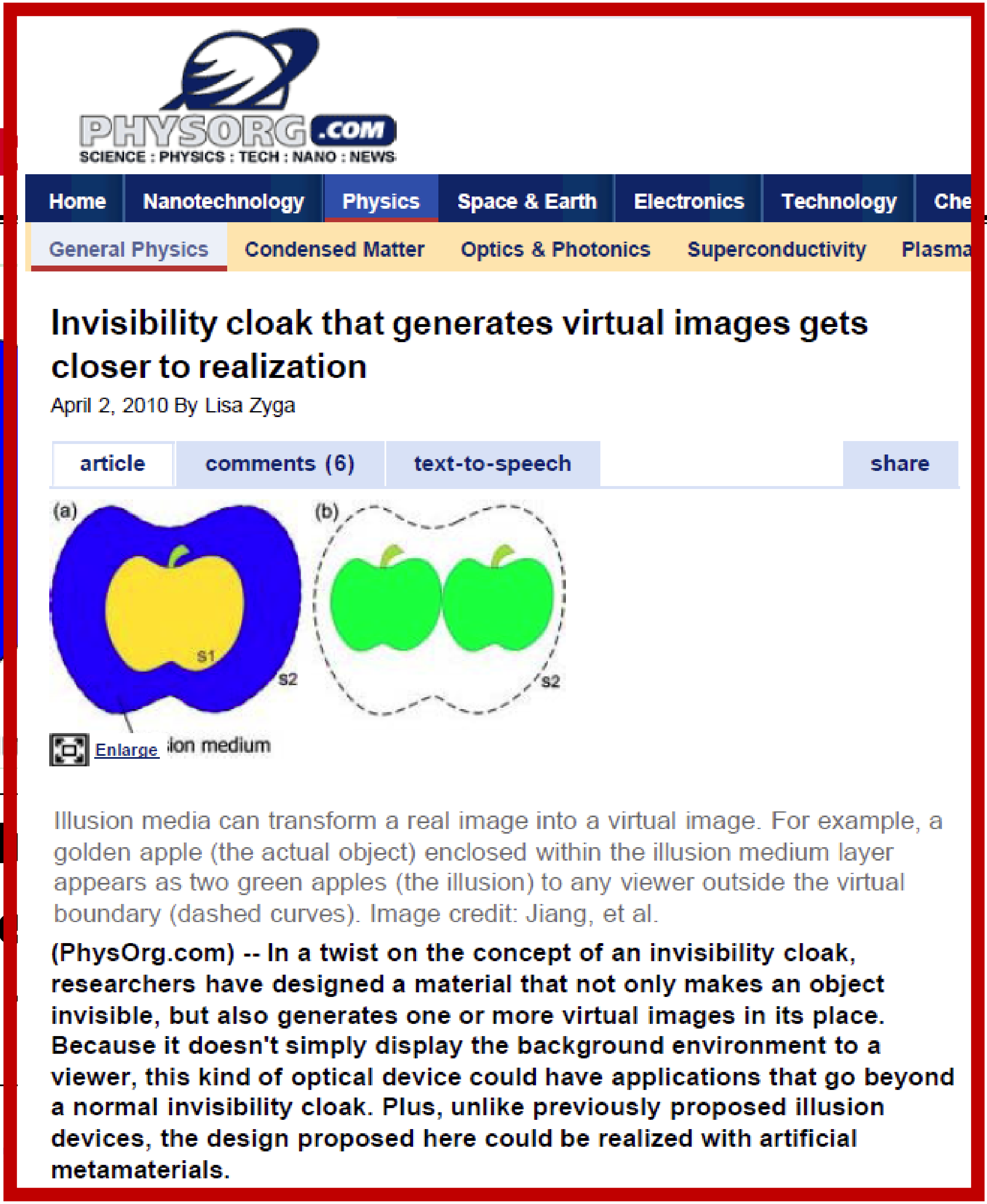
W. X. Jiang, T. J. Cui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Invisibility cloak that generates virtual images gets closer to realization

April 2, 2010 By Lisa Zyga

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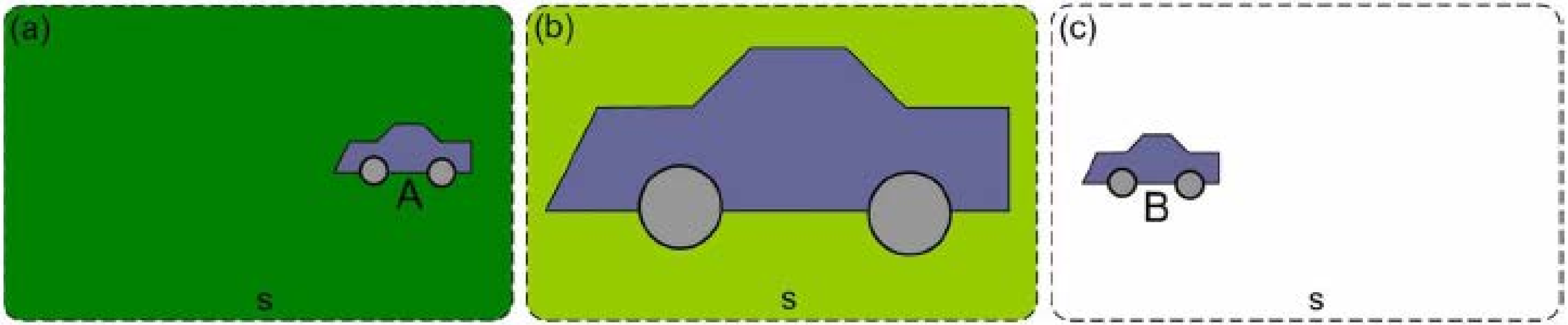
Illusion media can transform a real image into a virtual image. For example, a golden apple (the actual object) enclosed within the illusion medium layer appears as two green apples (the illusion) to any viewer outside the virtual boundary (dashed curves). Image credit: Jiang, et al.

(PhysOrg.com) -- In a twist on the concept of an invisibility cloak, researchers have designed a material that not only makes an object invisible, but also generates one or more virtual images in its place. Because it doesn't simply display the background environment to a viewer, this kind of optical device could have applications that go beyond a normal invisibility cloak. Plus, unlike previously proposed illusion devices, the design proposed here could be realized with artificial metamaterials.

Illusion Media



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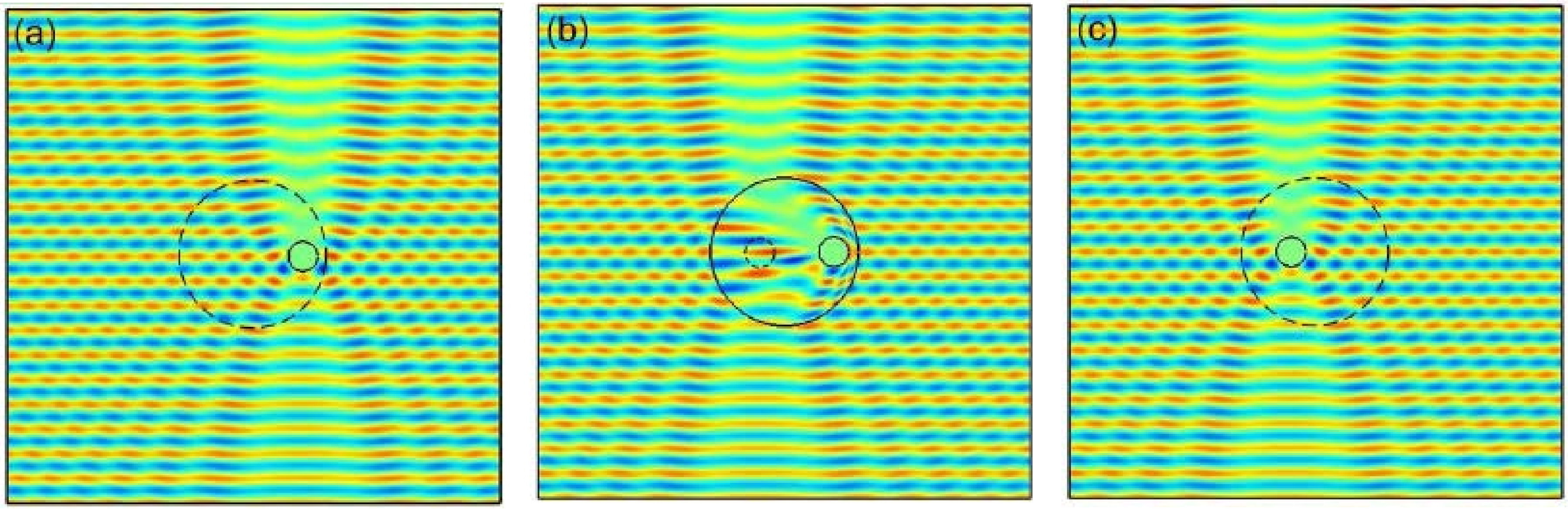
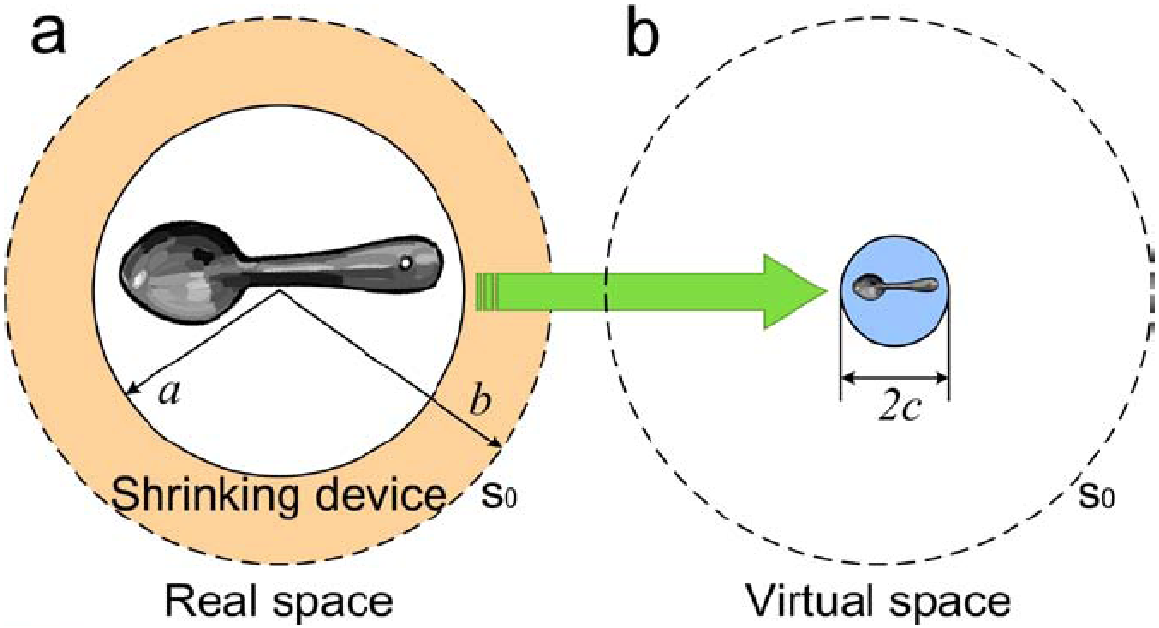


W. X. Jiang, T. J. Cui, *et* al., Optics Express, 18, 5161, 2010

Shrinking an Arbitrarily-Shaped Object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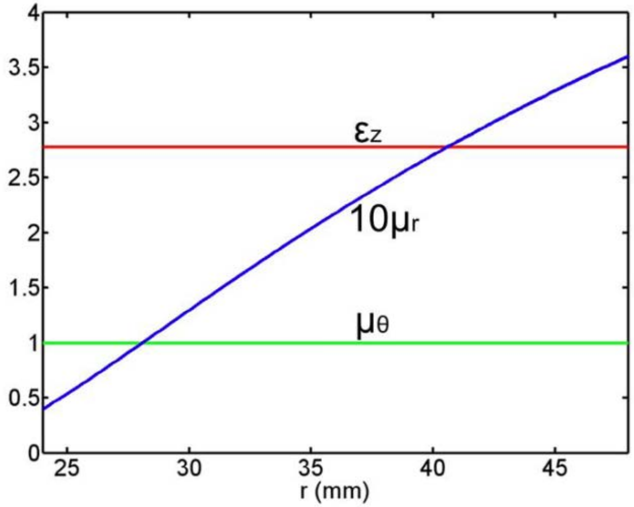

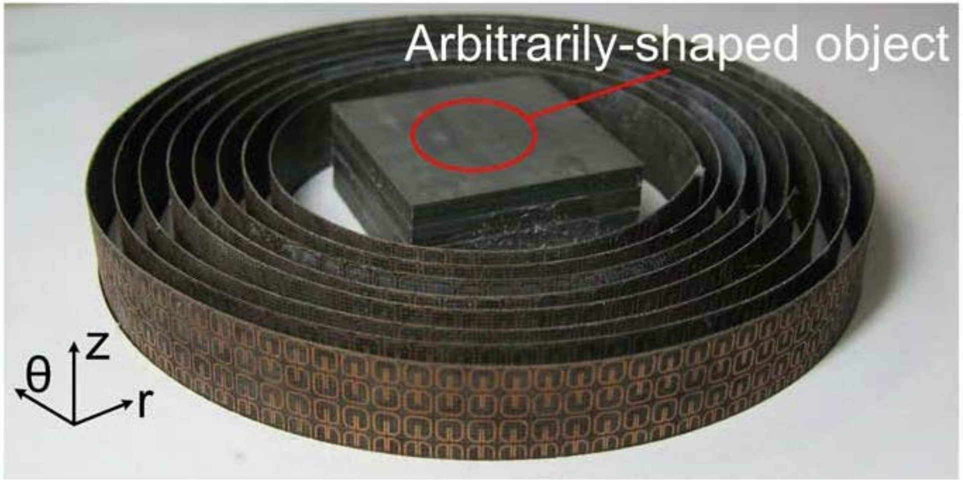
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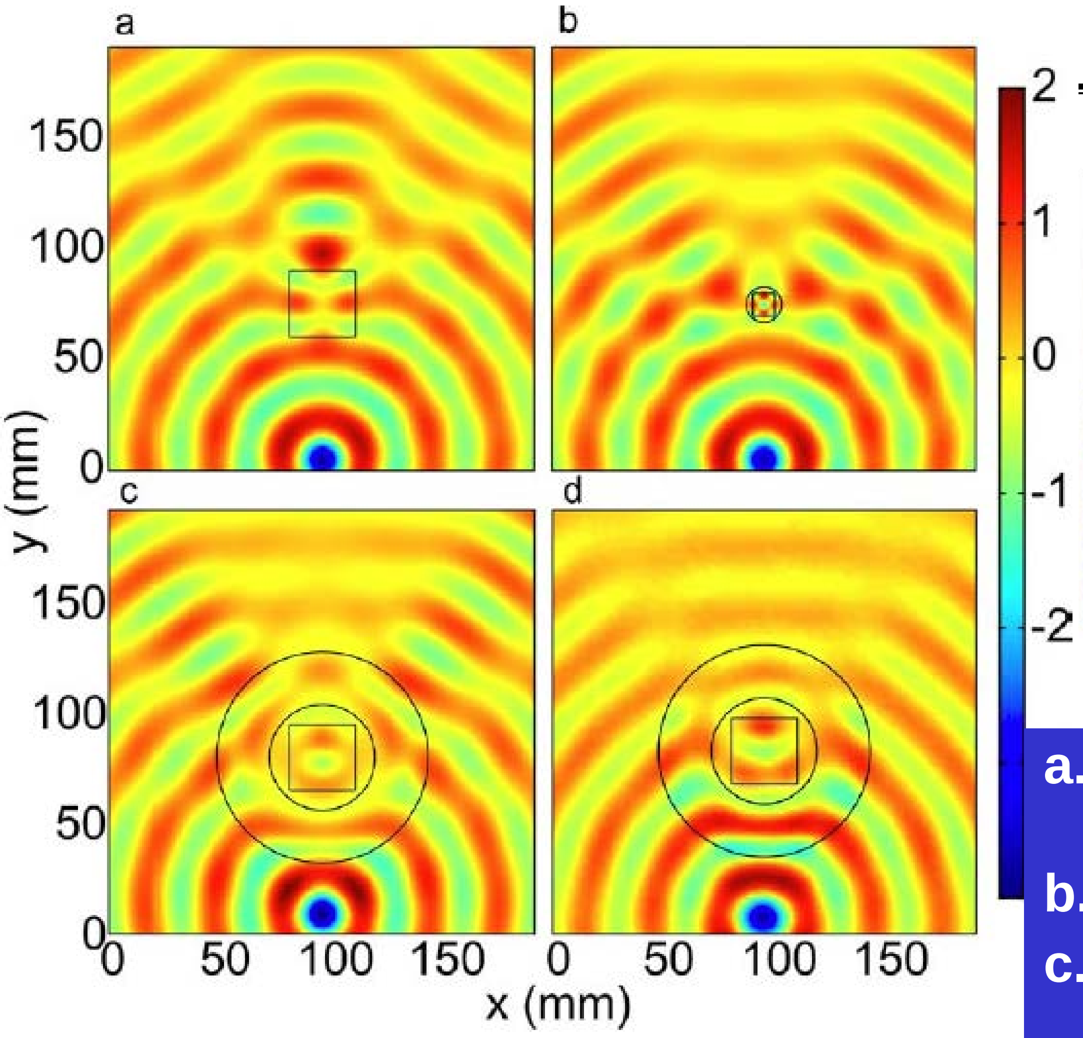
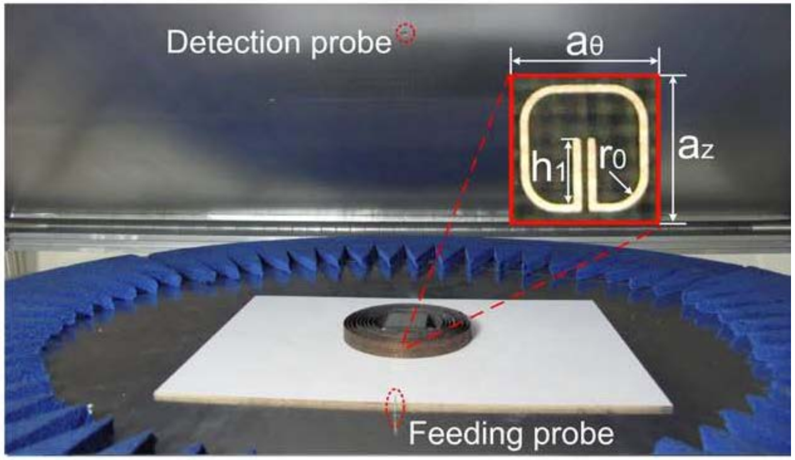
W. X. Jiang, T. J. Cui, *et* al., APL, 98, 204101, 2011




Detection probe
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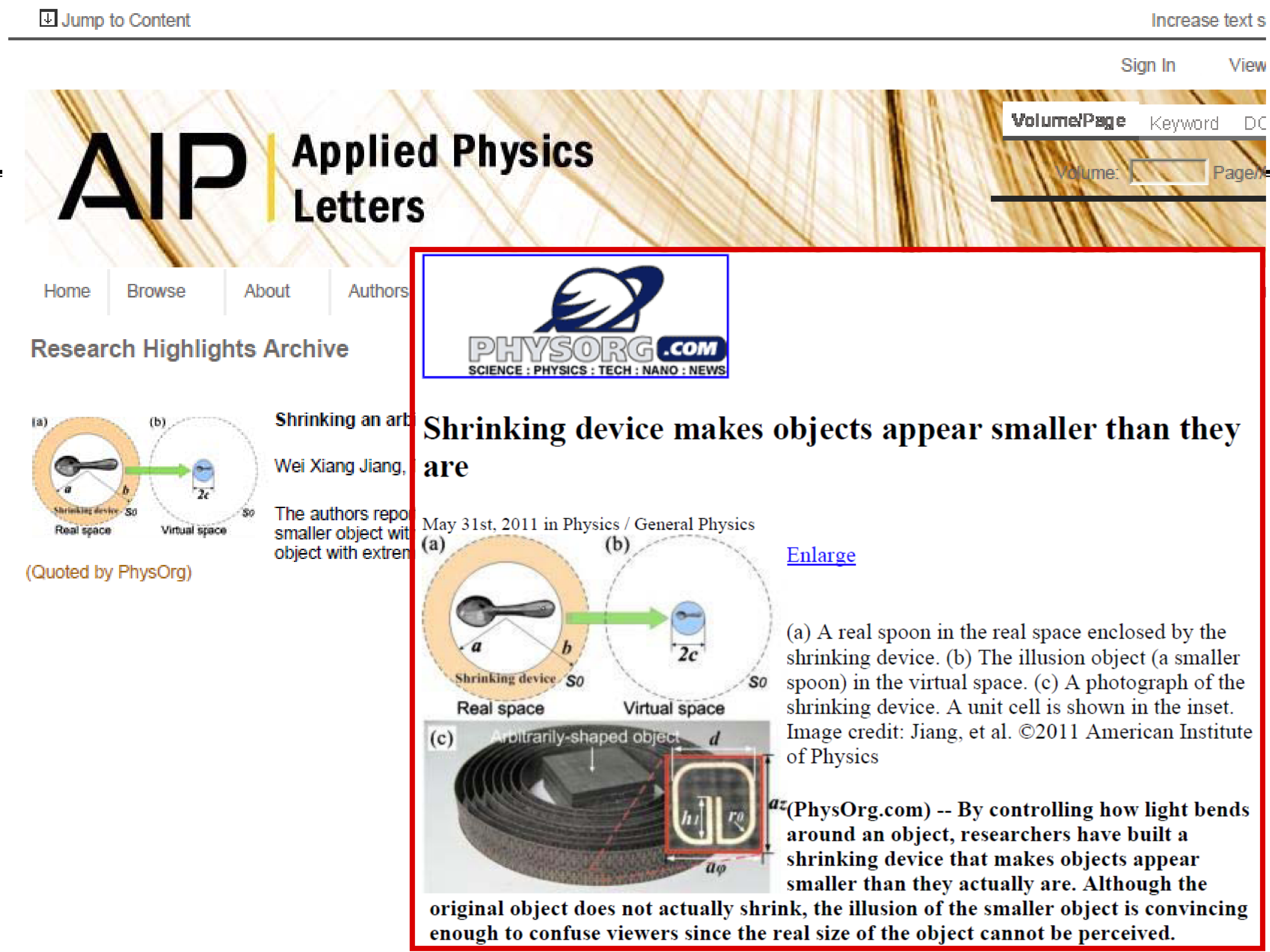
- a. Simulation: a dielectric target
- b. Simulation: virtual target
- c. Simulation: a dielectric target with illusion device
- d. Measurement



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Shrinking device makes objects appear smaller than they are

May 31st, 2011 in Physics / General Physics

(a) A real spoon in the real space enclosed by the shrinking device. (b) The illusion object (a smaller spoon) in the virtual space. (c) A photograph of the shrinking device. A unit cell is shown in the inset. Image credit: Jiang, et al. ©2011 American Institute of Physics

(PhysOrg.com) -- By controlling how light bends around an object, researchers have built a shrinking device that makes objects appear smaller than they actually are. Although the original object does not actually shrink, the illusion of the smaller object is convincing enough to confuse viewers since the real size of the object cannot be perceived.

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Real space
Virtual space

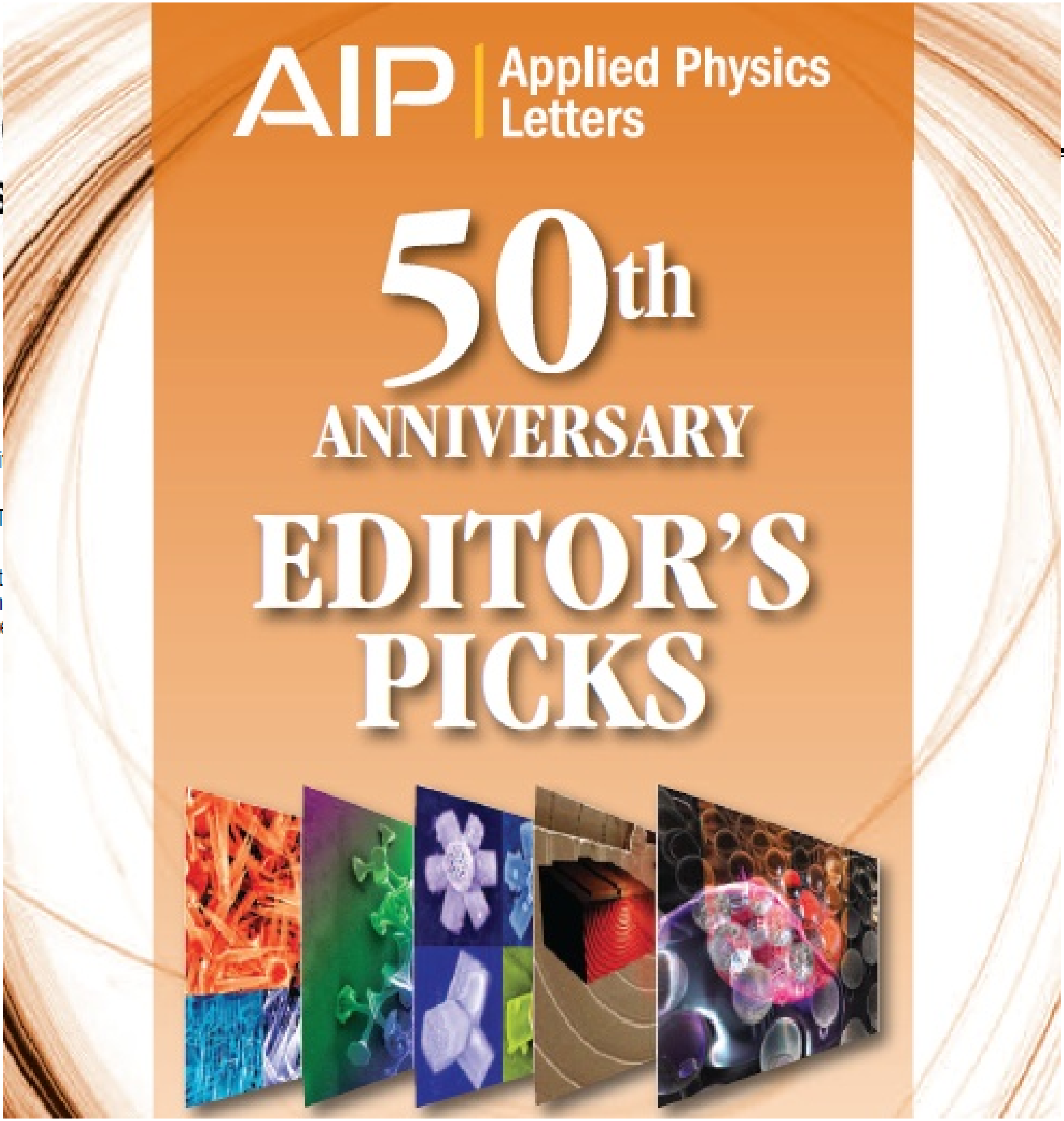
Research Highlights Archive

Shrinking an arbi

Wei Xiang Jiang, T

The authors report smaller object with object with extrem

(Quoted by PhysOrg)



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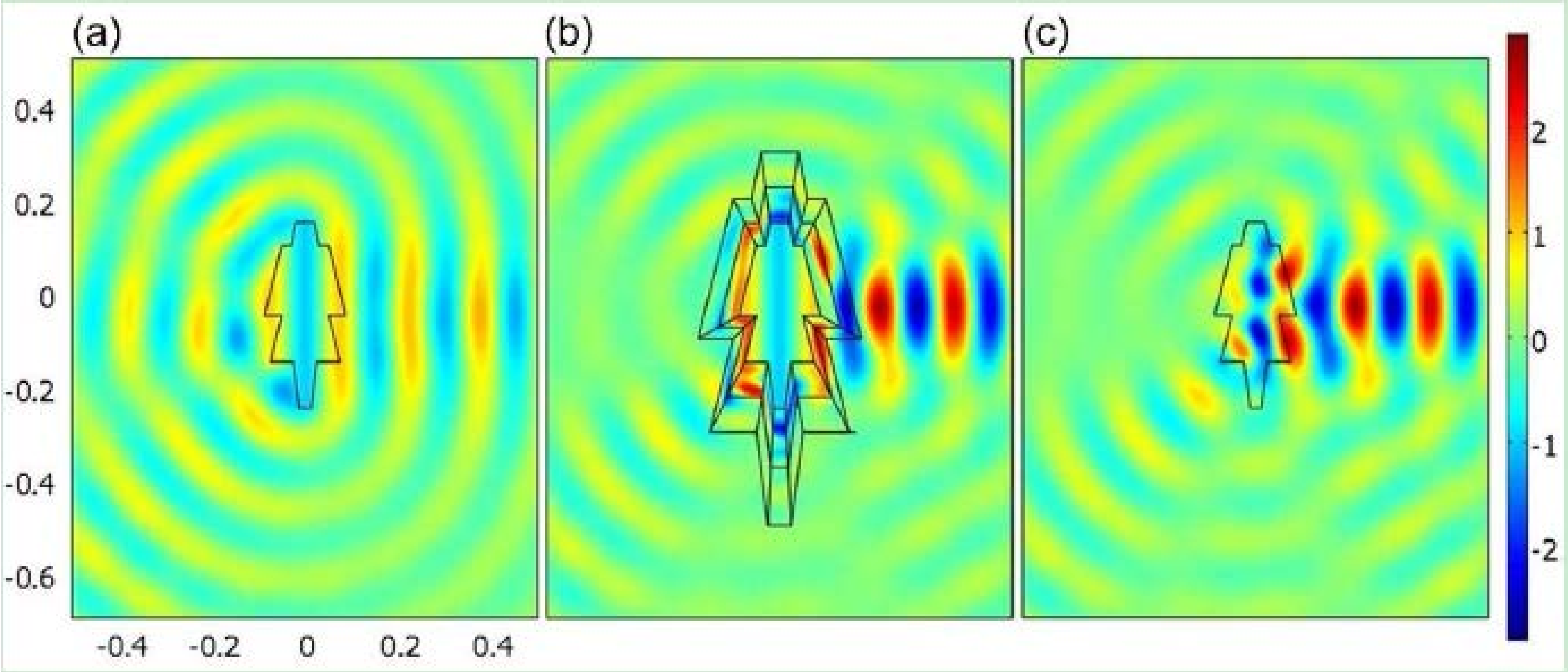
EDITOR'S PICKS

Radar Illusion

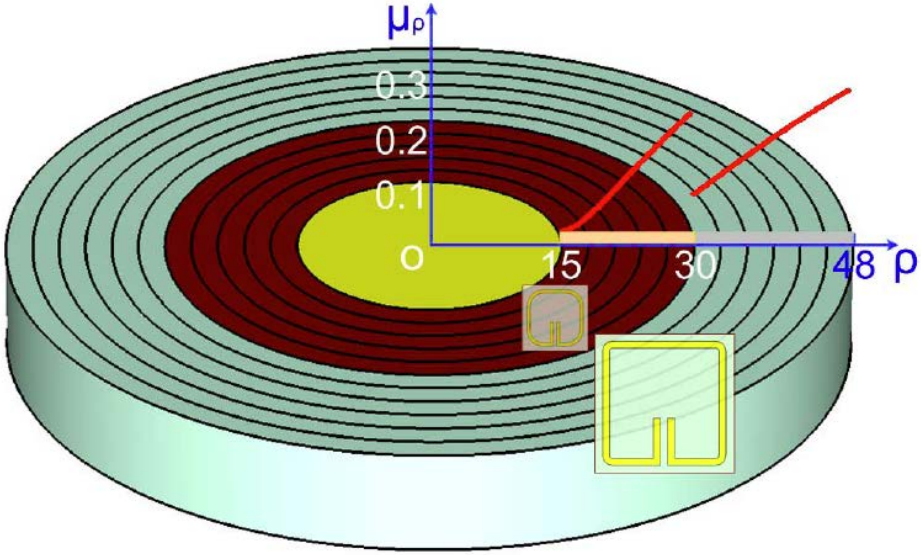


Metal Object is changed to Dielectric Object

No LHM, No Singularities

W. X. Jiang and T. J. Cui, Optics Express, 18, 11276, 2010

Convert Metallic Target to Dielectric Target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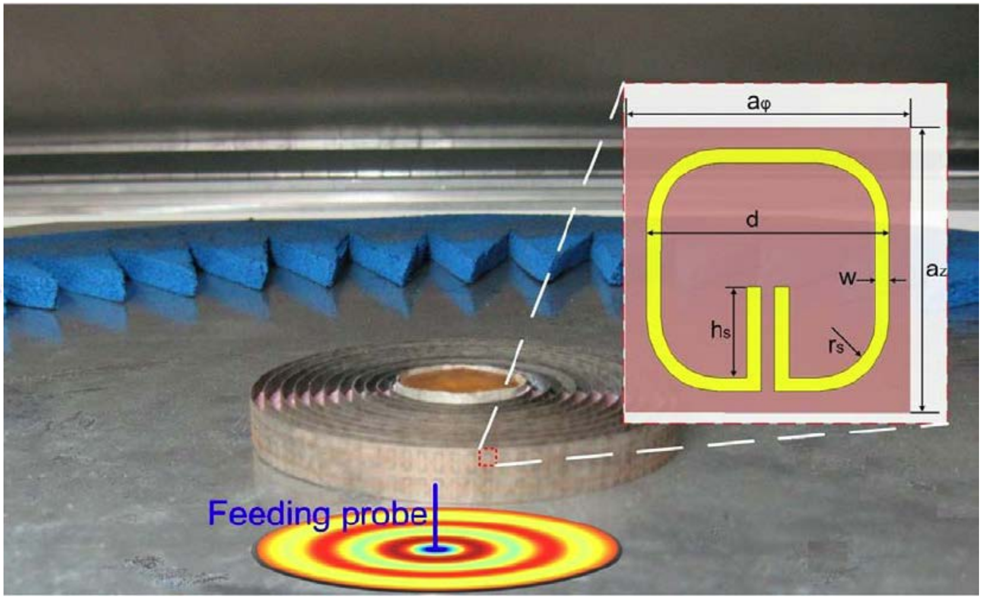
aφ
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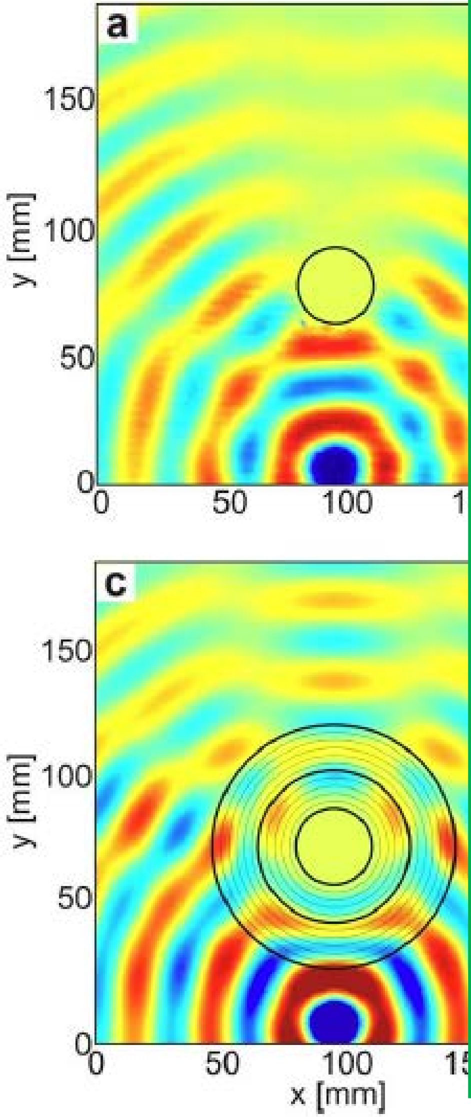
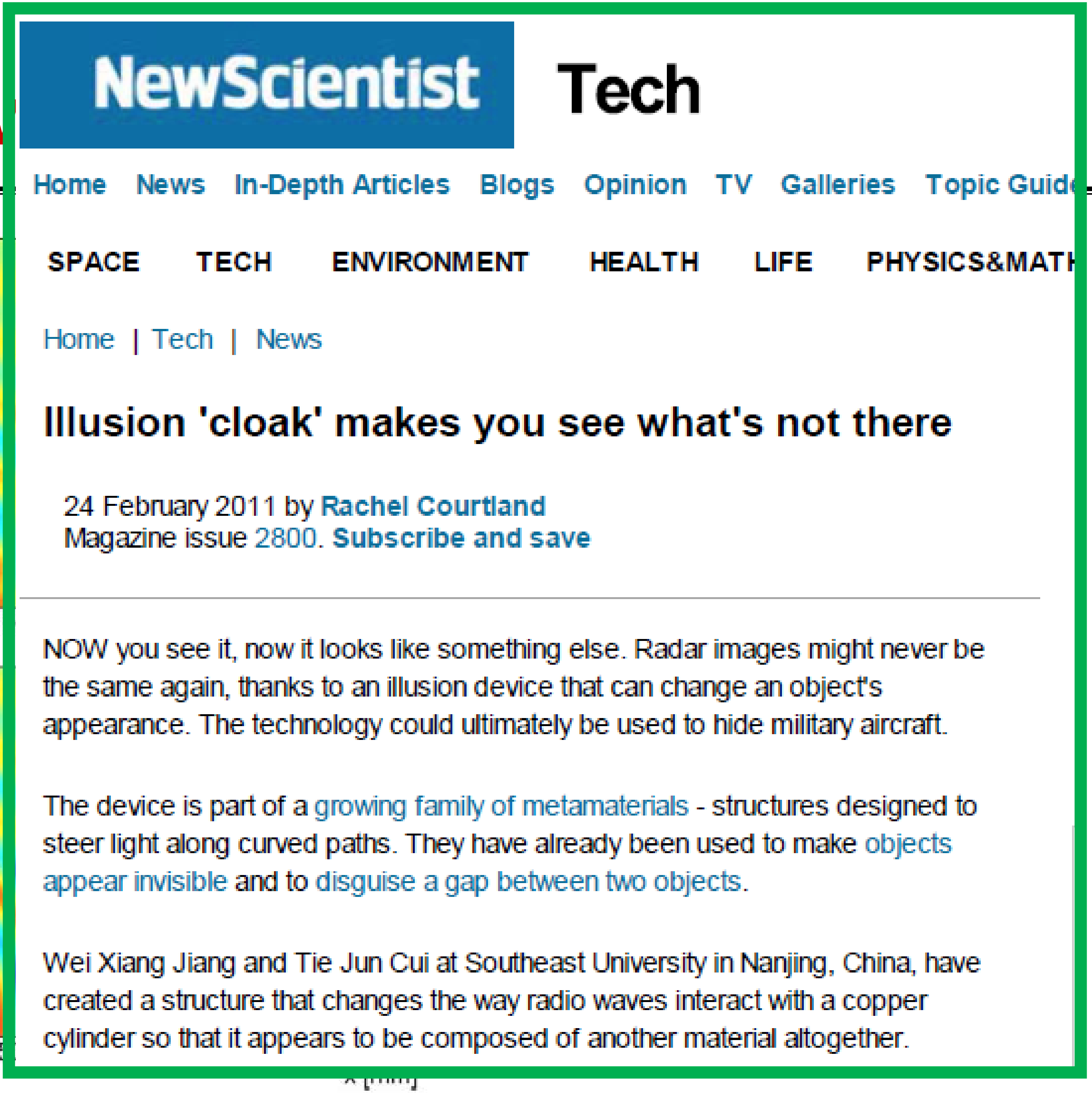
Feeding probe

W. X. Jiang and T. J. Cui, PRE, 83, 026601, 2011

(Reported: New Scientist)

Convert M

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Illusion 'cloak' makes you see what's not there

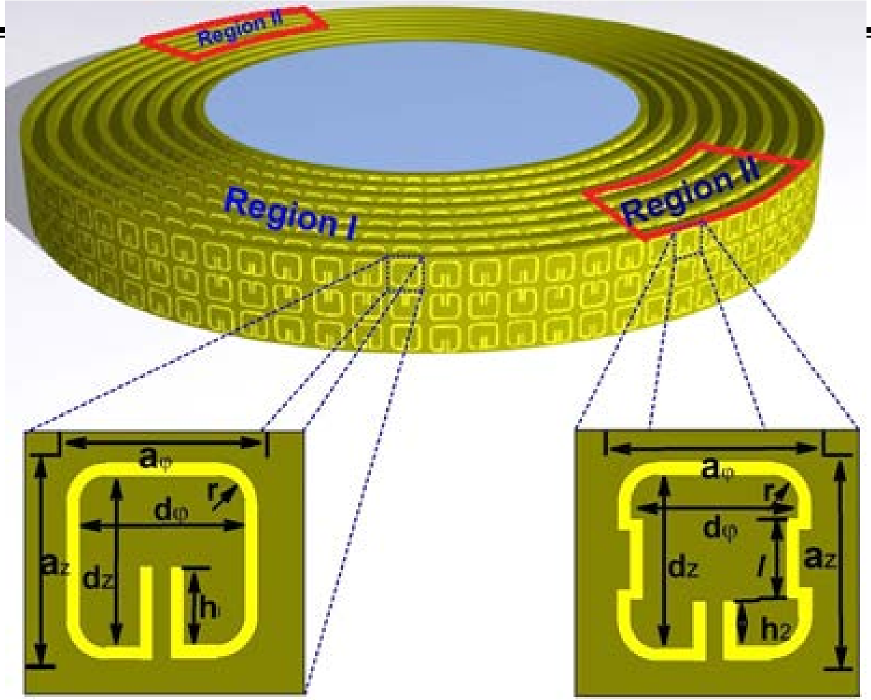
24 February 2011 by **Rachel Courtland**
Magazine issue 2800. **Subscribe and save**

NOW you see it, now it looks like something else. Radar images might never be the same again, thanks to an illusion device that can change an object's appearance. The technology could ultimately be used to hide military aircraft.

The device is part of a growing family of metamaterials - structures designed to steer light along curved paths. They have already been used to make objects appear invisible and to disguise a gap between two objects.

Wei Xiang Jiang and Tie Jun Cui at Southeast University in Nanjing, China, have created a structure that changes the way radio waves interact with a copper cylinder so that it appears to be composed of another material altogether.

Illusion optics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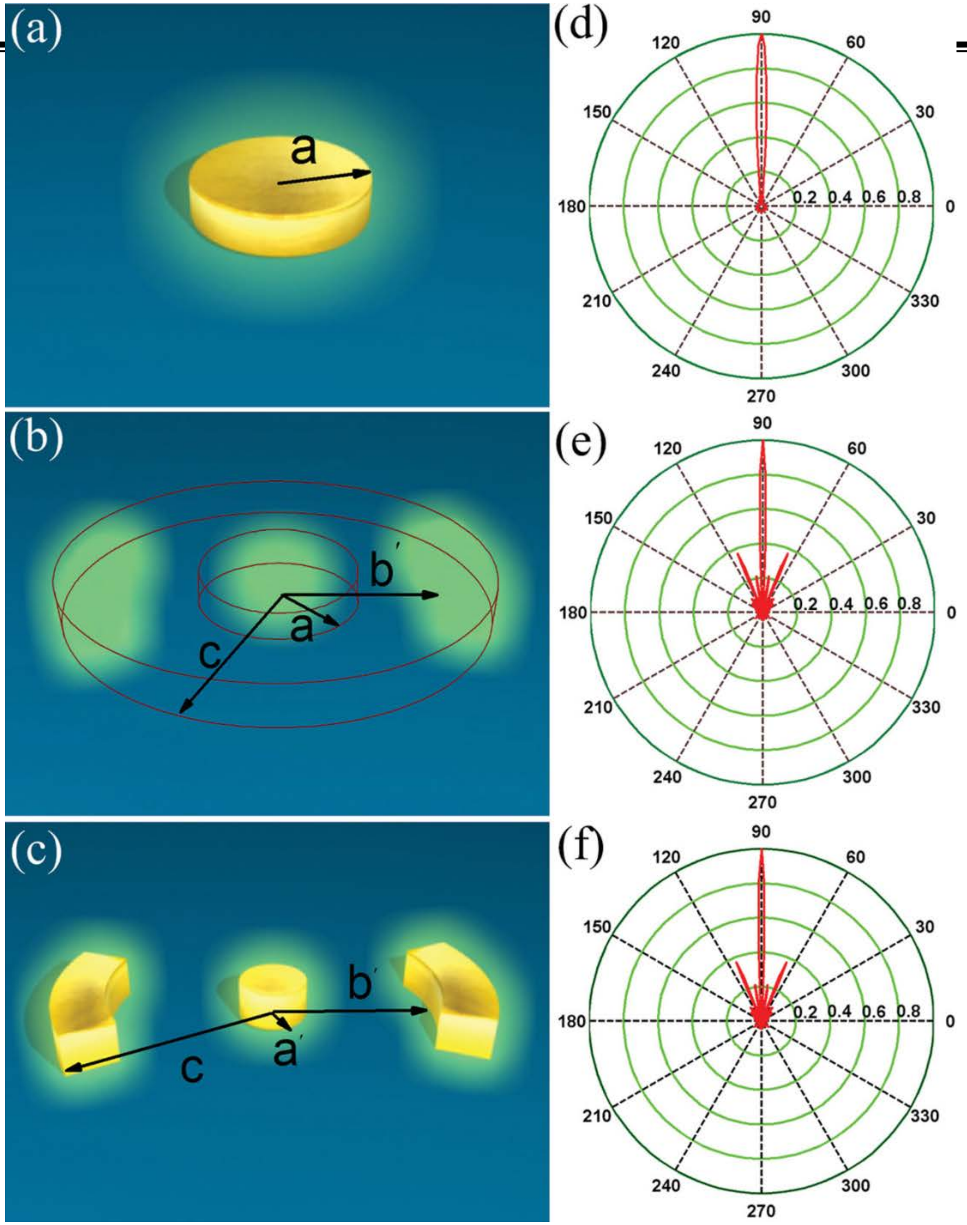
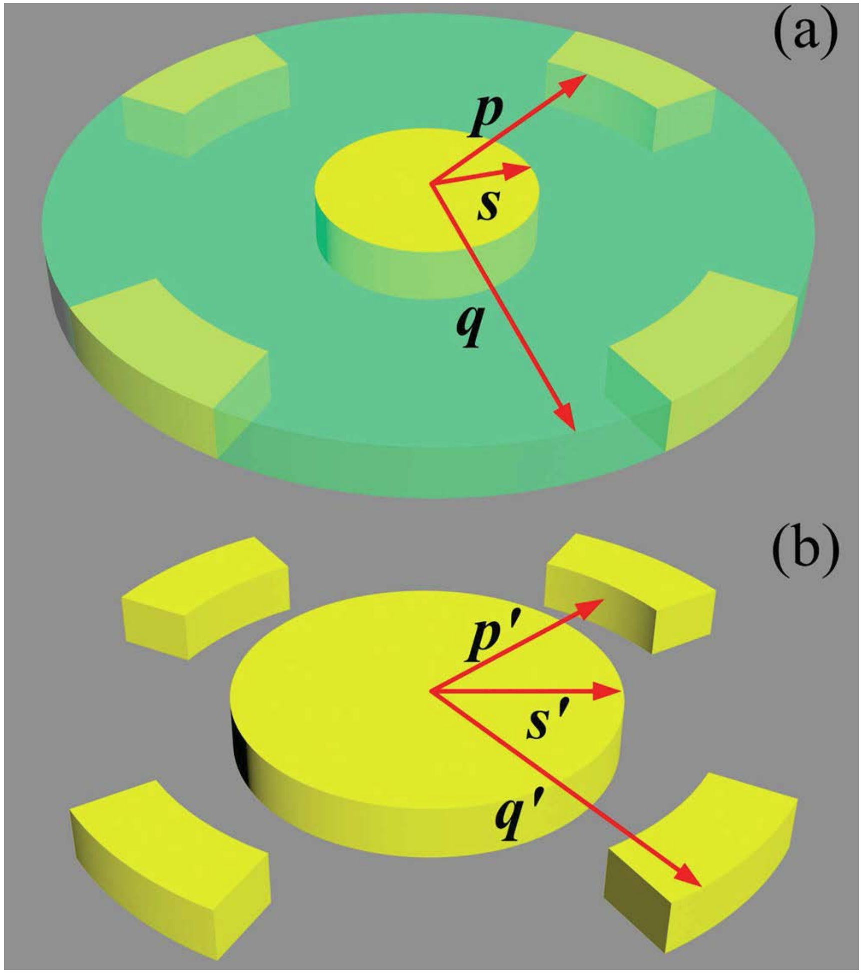
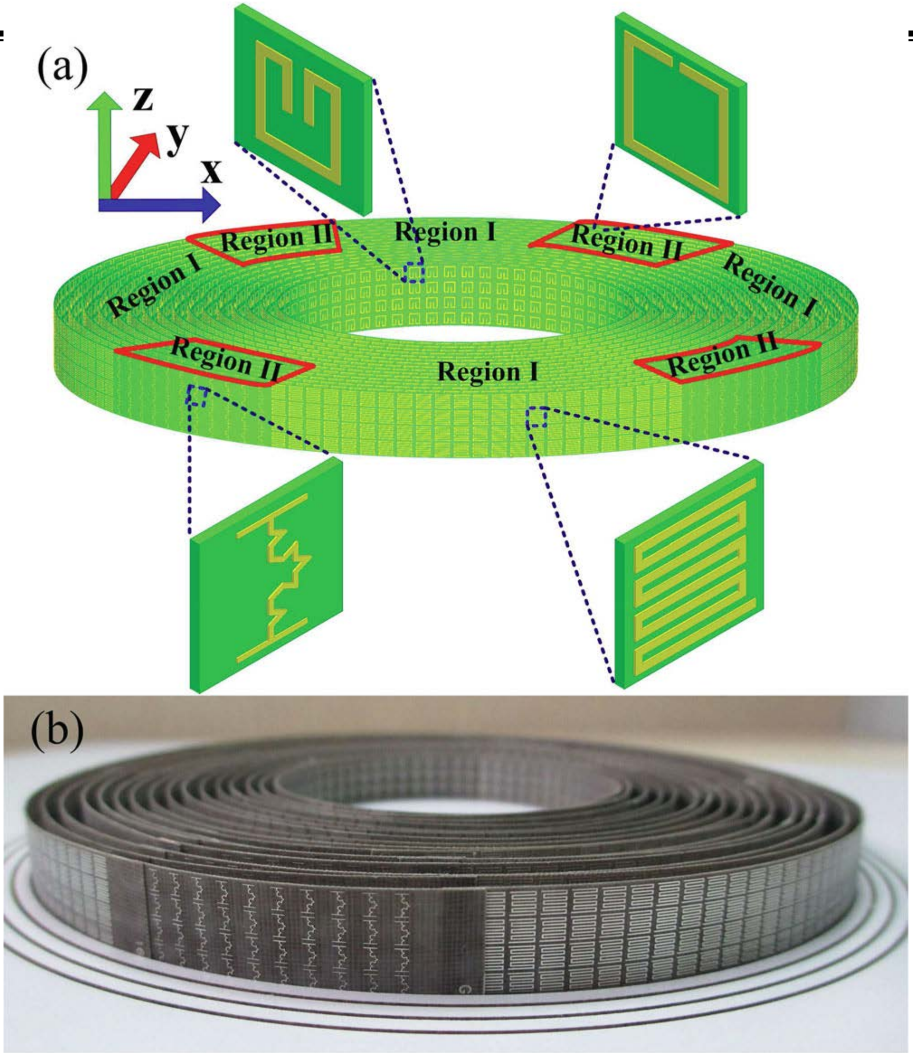


通过幻觉光学变换，使原目标缩小，并产生鬼影。

Jiang et al., Adv. Fun. Mat., 23, 4028, 2013（影响因子：10.8）

Illusion optics




(a)
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Region II
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Region II
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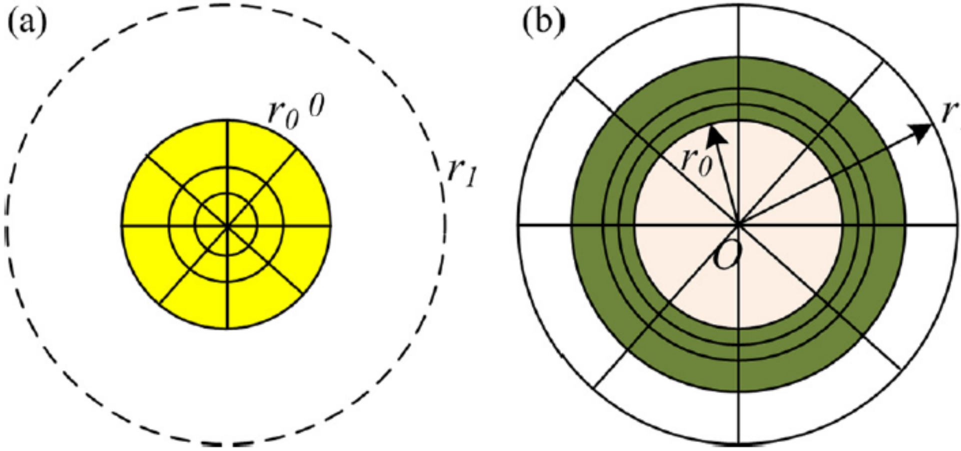
(b)

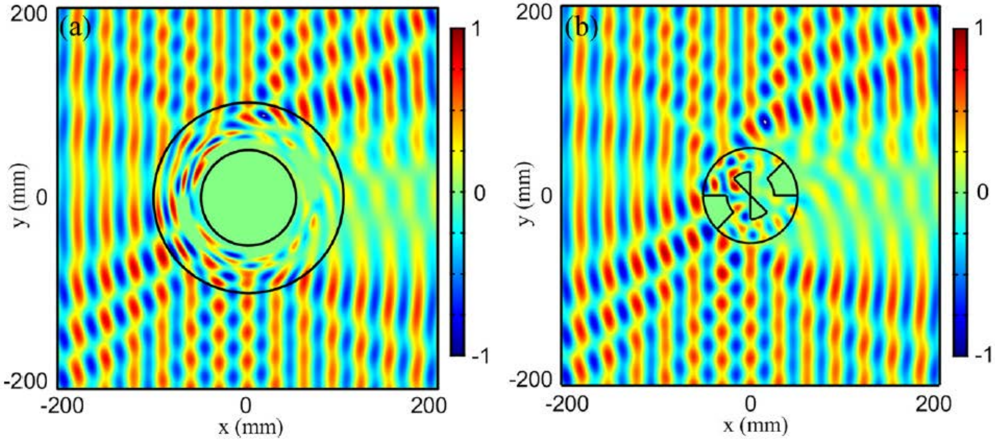
Superscattering

Xu et al., Adv. Opt. Mat., 2, 572, 2014

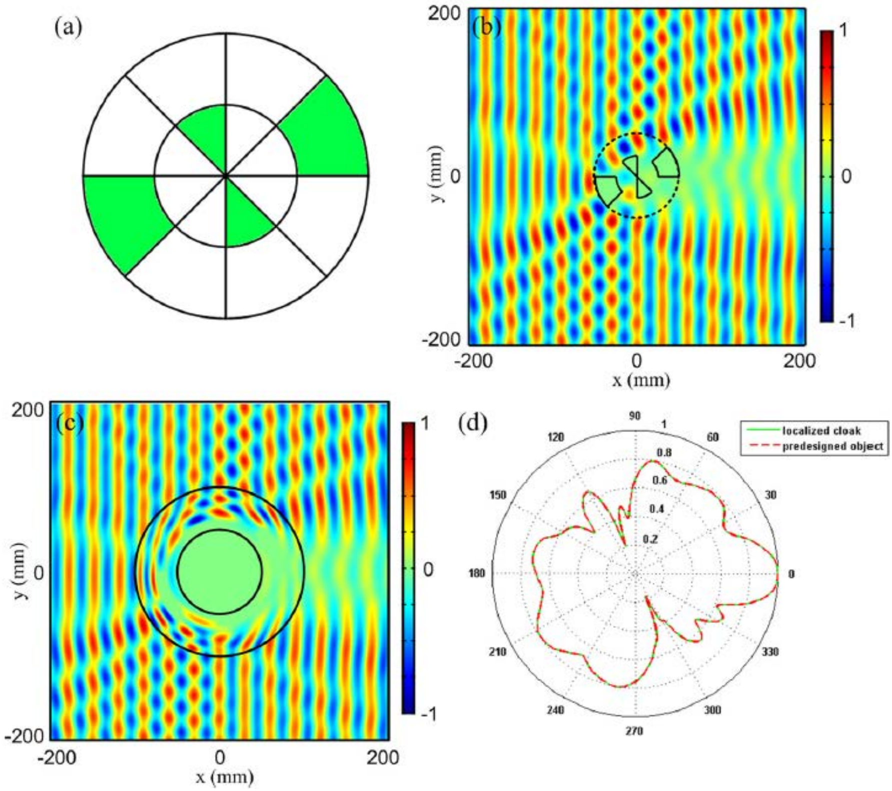
Localized transformation optics



Design scheme of localized TO device



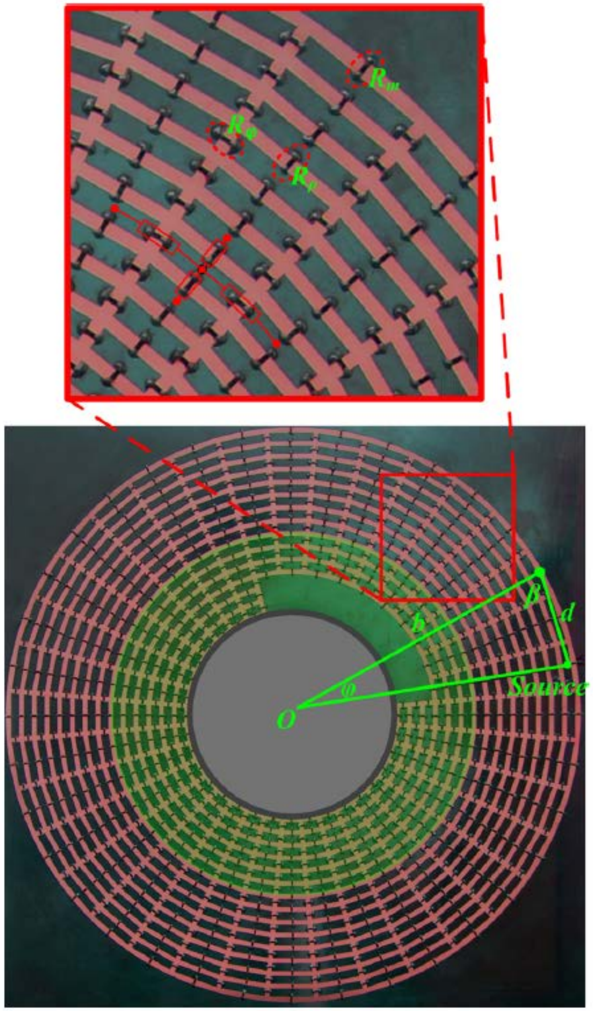
Localized illusion device



Localized invisible cloak

Appl. Phys. Lett. 103, 214104, 2014

Localized transformation optics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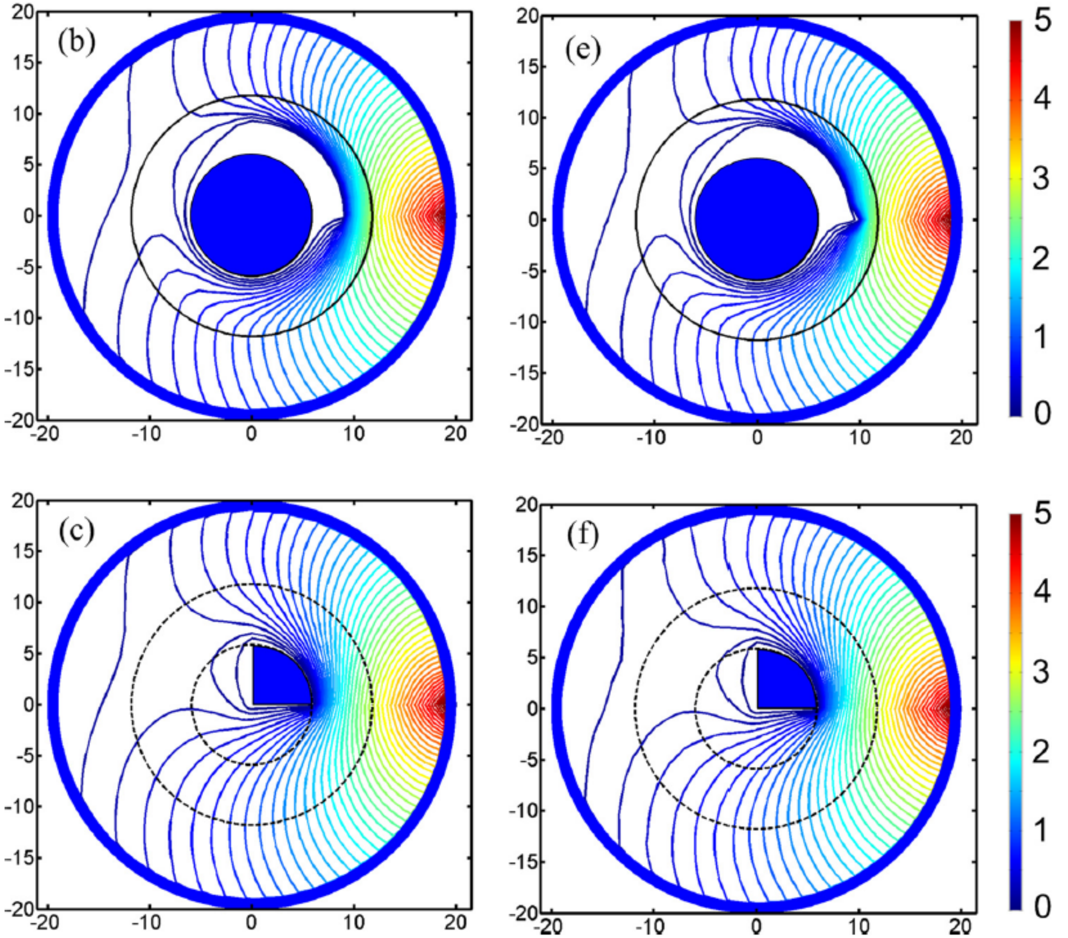
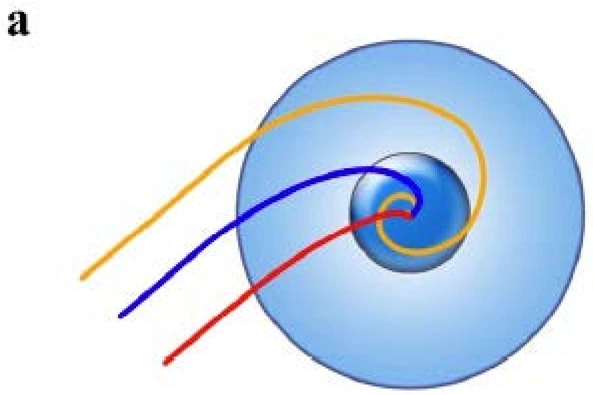
Fabricated sample



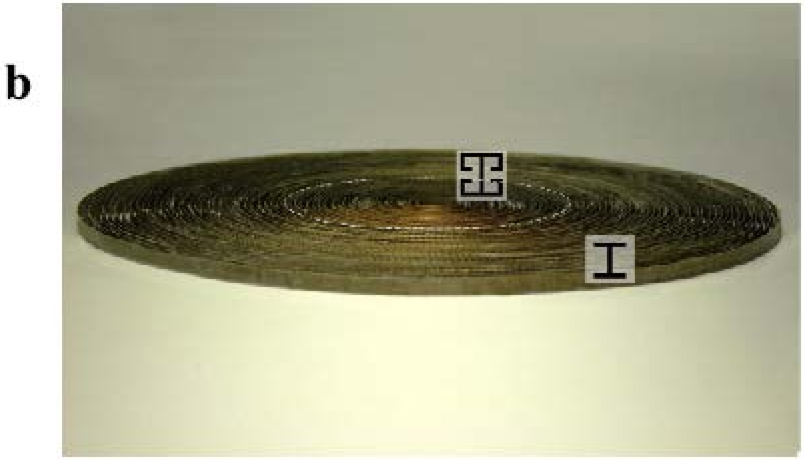
Simulation and experiment results

Electromagnetic Black Hole



$$\epsilon(r) = \begin{cases} \epsilon_b, & r > R \\ \epsilon_s(r) = \epsilon_b (R/r)^2, & R_c \le r \le R \\ \epsilon_c + i\gamma, & r < R_c \end{cases}$$

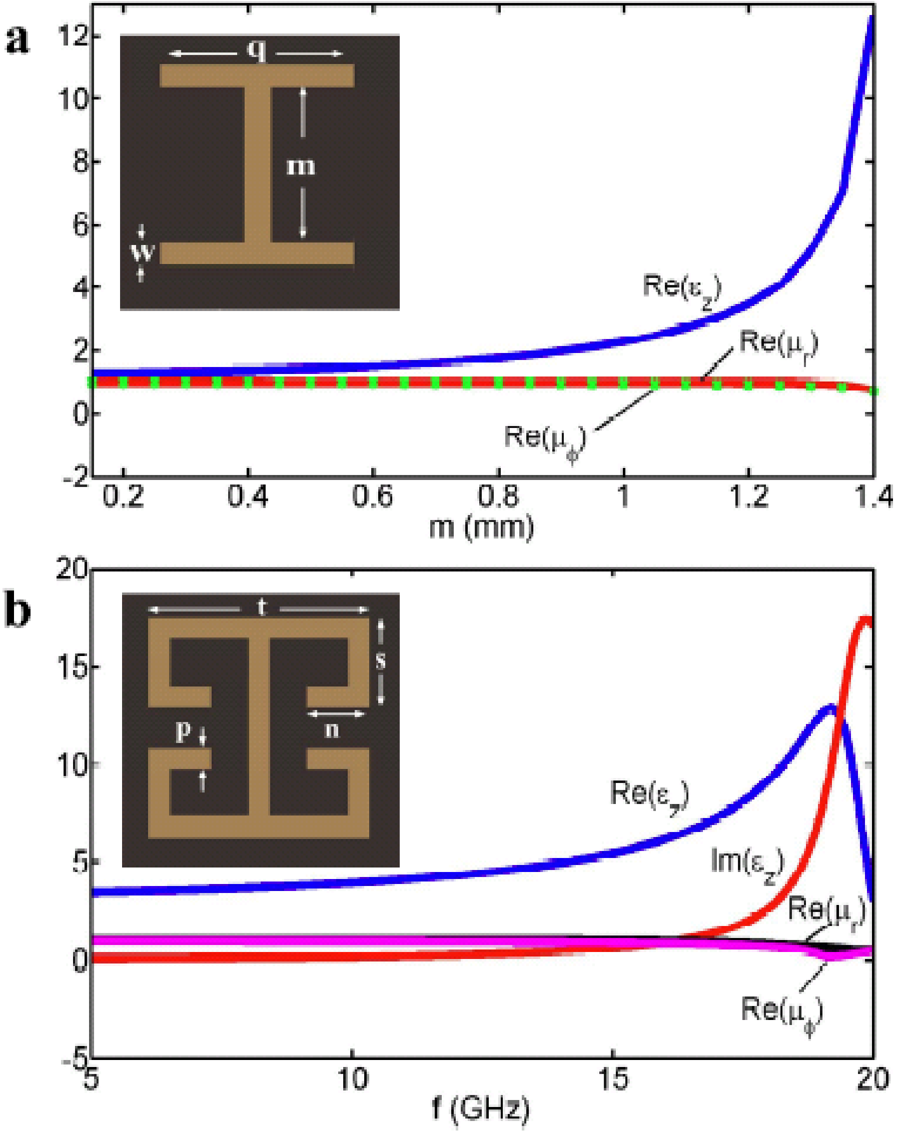
Narimanov, Kildishev, *APL* 95, 041106 (2009).

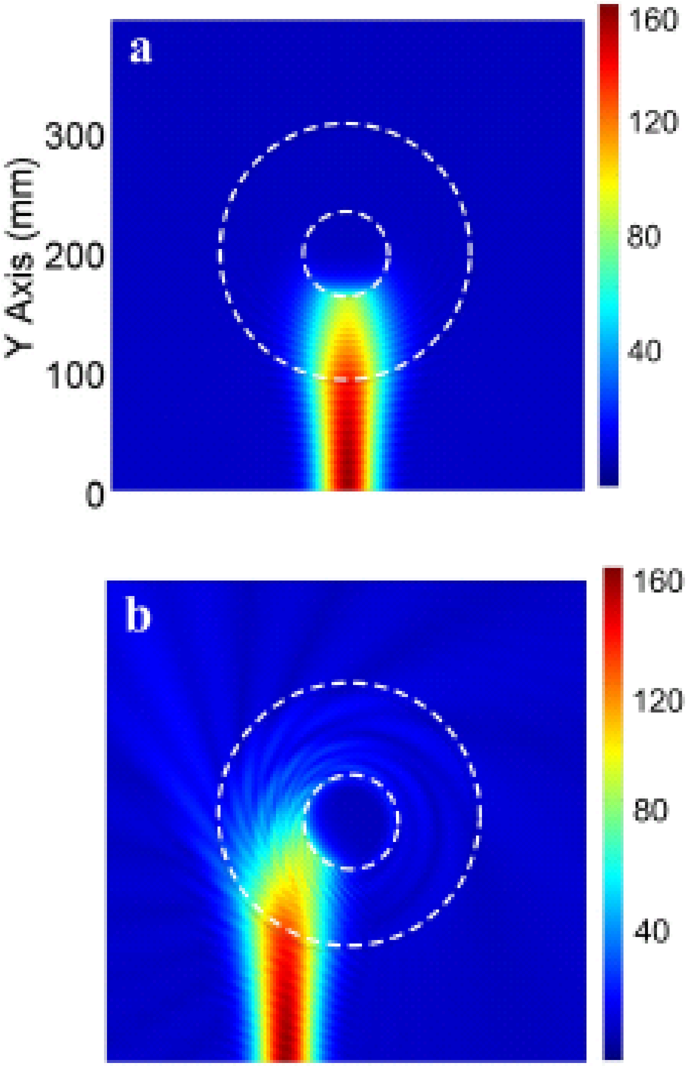


Cheng, Cui, Jiang, Cai, *New Journal of Physics*, Vol.12, 063006, 2010

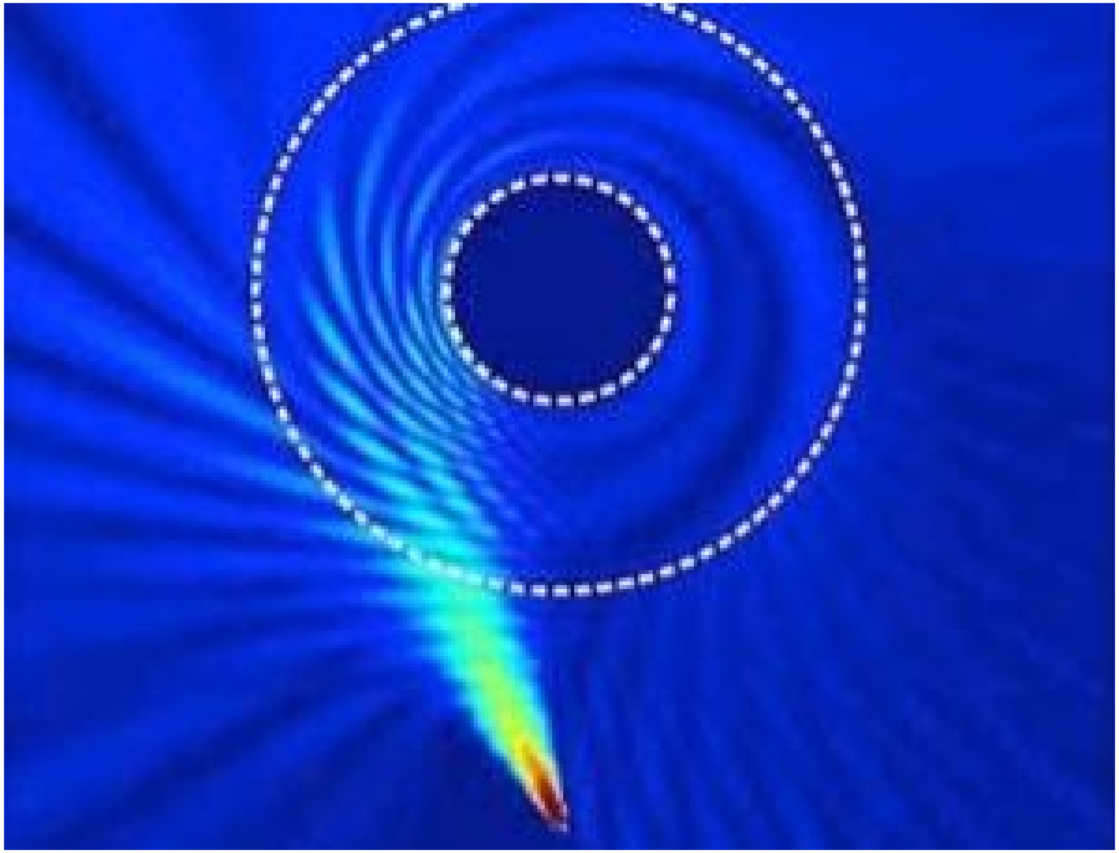
- **Mimic the gravitational fields;**
- **All EM waves hitting it will be trapped spirally by the core and then totally absorbed;**
- **Behaves like a black body in the thermal dynamics;**
- **Not a general-relativity black hole.**

Electromagnetic Black Hole

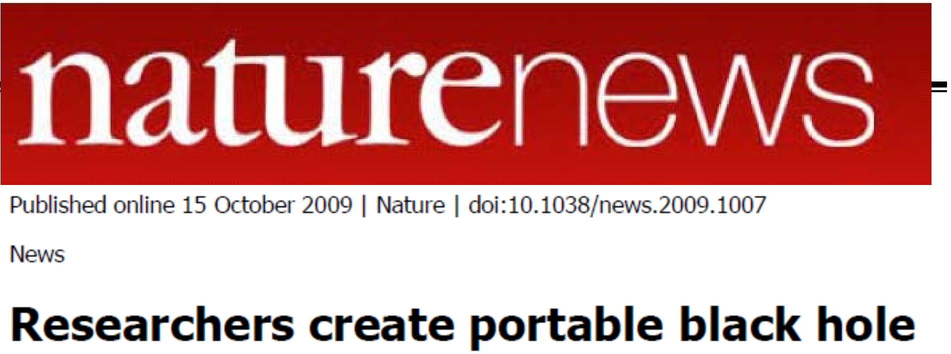




Electromagnetic Black Hole



“Best of 2010” in NJP

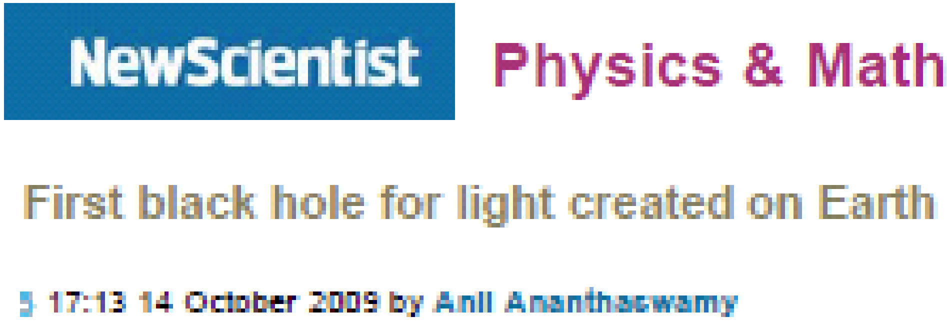


naturenews

Published online 15 October 2009 | Nature | doi:10.1038/news.2009.1007

News

Researchers create portable black hole

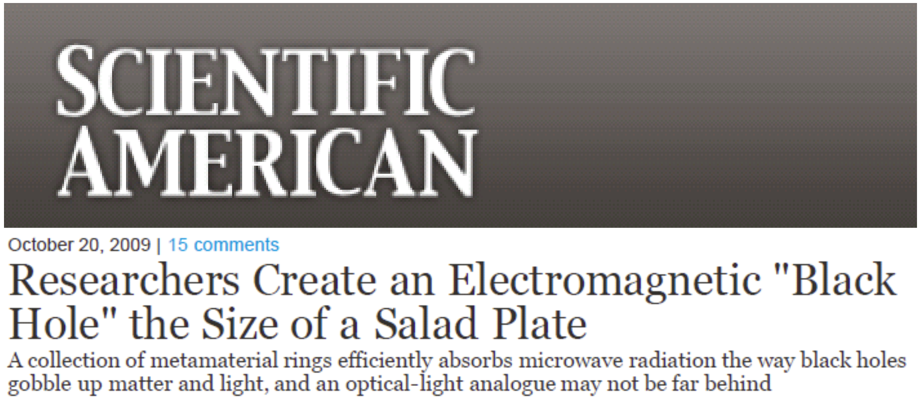


NewScientist

Physics & Math

First black hole for light created on Earth

17:13 14 October 2009 by Anil Ananthaswamy

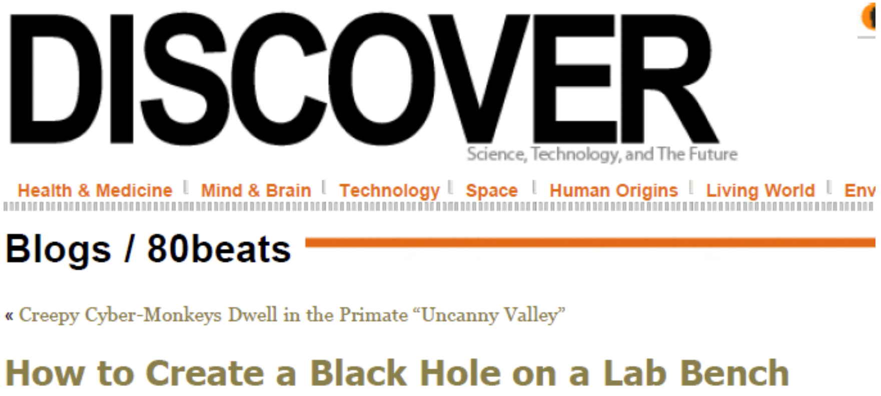


SCIENTIFIC AMERICAN

October 20, 2009 | 15 comments

Researchers Create an Electromagnetic "Black Hole" the Size of a Salad Plate

A collection of metamaterial rings efficiently absorbs microwave radiation the way black holes gobble up matter and light, and an optical-light analogue may not be far behind



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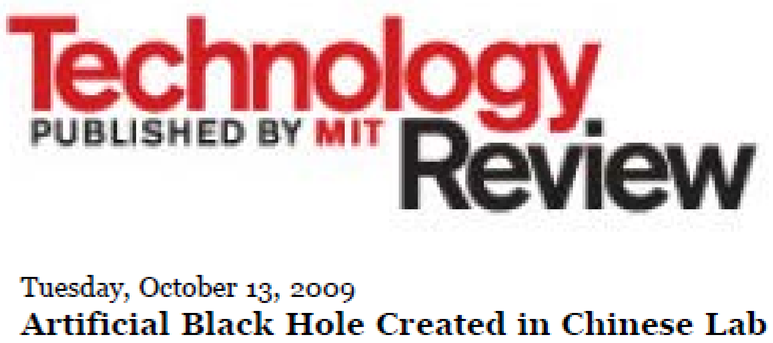
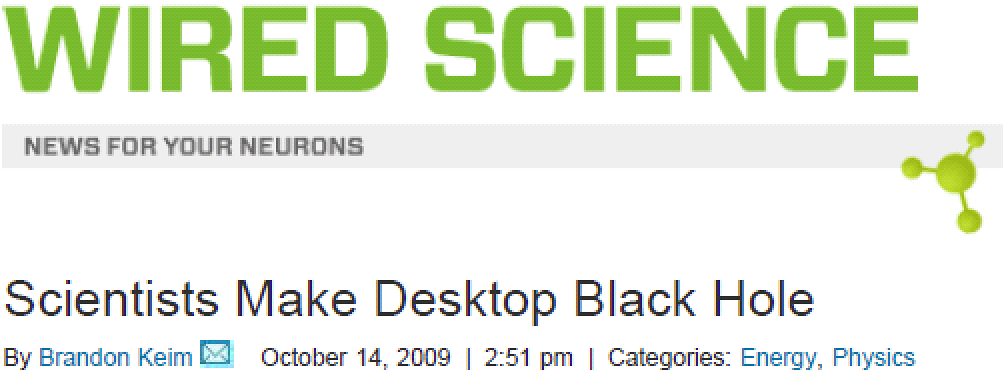
How to Create a Black Hole on a Lab Bench



Technology Review
PUBLISHED BY MIT

Tuesday, October 13, 2009

Artificial Black Hole Created in Chinese Lab



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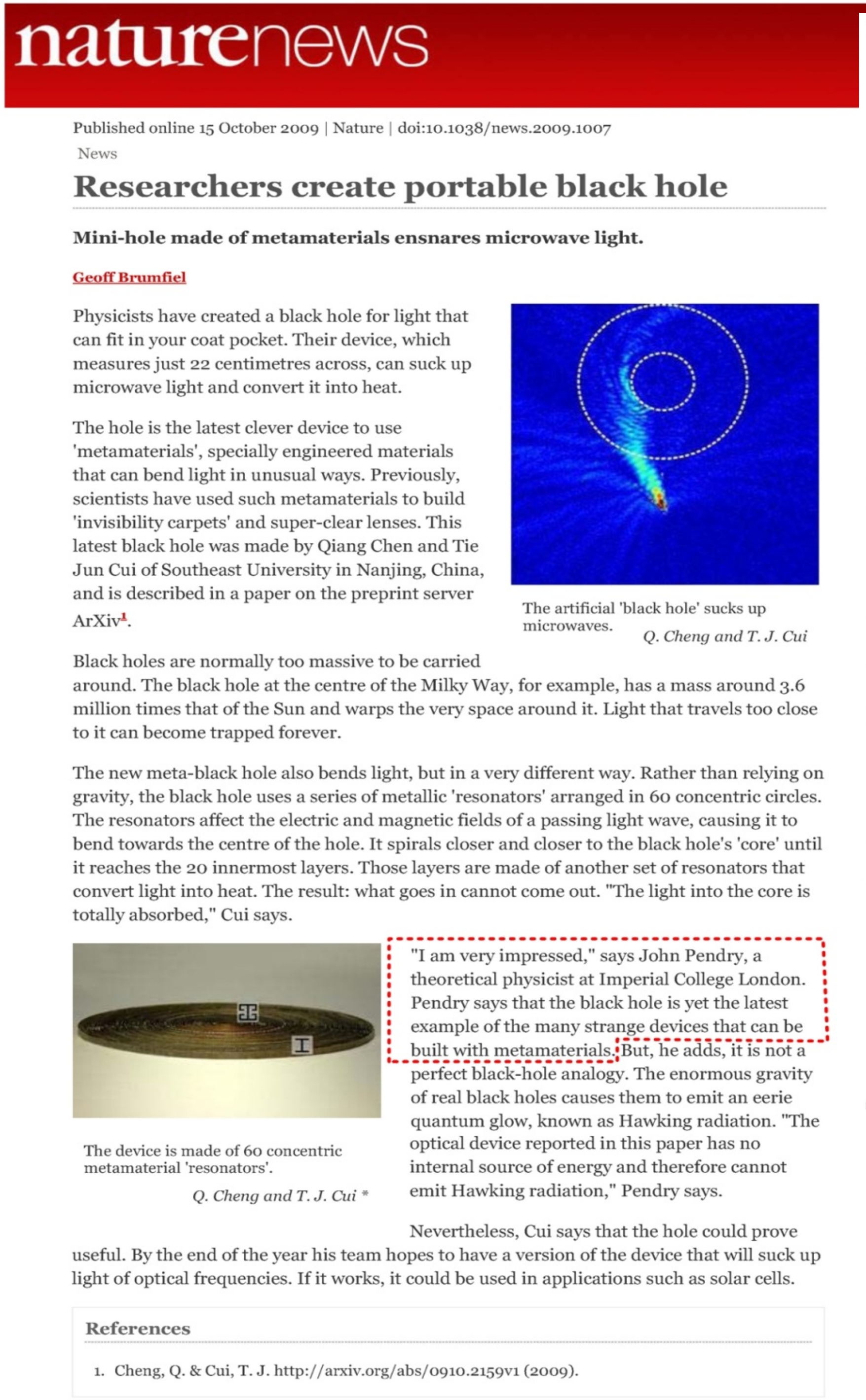
Scientists Make Desktop Black Hole

By Brandon Keim October 14, 2009 | 2:51 pm | Categories: Energy, Physics



naturenews

Published online 15 October 2009 | Nature | doi:10.1038/news.2009.1007

News

Researchers create portable black hole

Mini-hole made of metamaterials ensnares microwave light.

Geoff Brumfiel

Physicists have created a black hole for light that can fit in your coat pocket. Their device, which measures just 22 centimetres across, can suck up microwave light and convert it into heat.

The hole is the latest clever device to use 'metamaterials', specially engineered materials that can bend light in unusual ways. Previously, scientists have used such metamaterials to build 'invisibility carpets' and super-clear lenses. This latest black hole was made by Qiang Chen and Tie Jun Cui of Southeast University in Nanjing, China, and is described in a paper on the preprint server ArXiv[1].

The artificial 'black hole' sucks up microwaves.

Q. Cheng and T. J. Cui

Black holes are normally too massive to be carried around. The black hole at the centre of the Milky Way, for example, has a mass around 3.6 million times that of the Sun and warps the very space around it. Light that travels too close to it can become trapped forever.

The new meta-black hole also bends light, but in a very different way. Rather than relying on gravity, the black hole uses a series of metallic 'resonators' arranged in 60 concentric circles. The resonators affect the electric and magnetic fields of a passing light wave, causing it to bend towards the centre of the hole. It spirals closer and closer to the black hole's 'core' until it reaches the 20 innermost layers. Those layers are made of another set of resonators that convert light into heat. The result: what goes in cannot come out. "The light into the core is totally absorbed," Cui says.

The device is made of 60 concentric metamaterial 'resonators'.

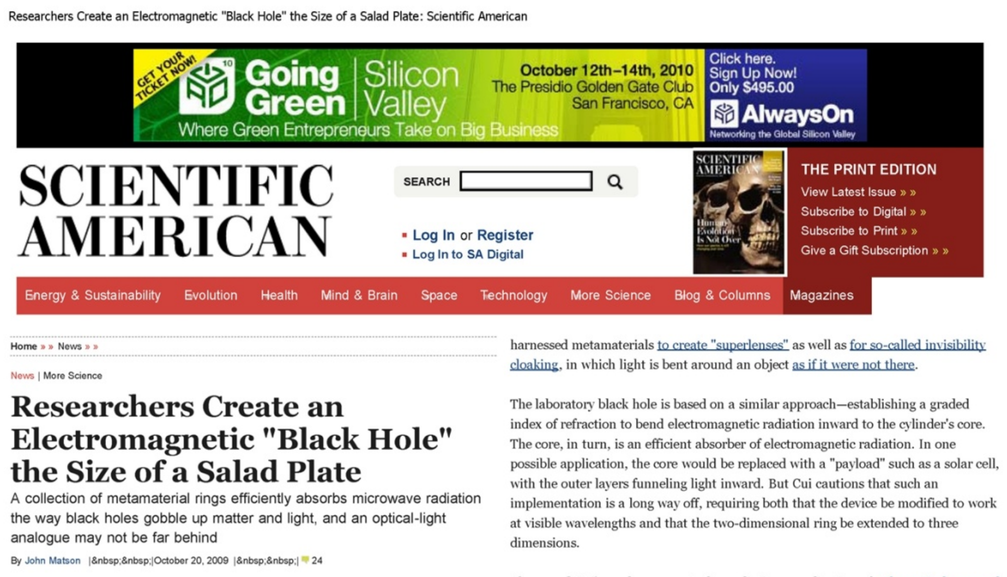
*Q. Cheng and T. J. Cui **

"I am very impressed," says John Pendry, a theoretical physicist at Imperial College London. Pendry says that the black hole is yet the latest example of the many strange devices that can be built with metamaterials. But, he adds, it is not a perfect black-hole analogy. The enormous gravity of real black holes causes them to emit an eerie quantum glow, known as Hawking radiation. "The optical device reported in this paper has no internal source of energy and therefore cannot emit Hawking radiation," Pendry says.

Nevertheless, Cui says that the hole could prove useful. By the end of the year his team hopes to have a version of the device that will suck up light of optical frequencies. If it works, it could be used in applications such as solar cells.

References

1. Cheng, Q. & Cui, T. J. http://arxiv.org/abs/0910.2159v1 (2009).



Researchers Create an Electromagnetic "Black Hole" the Size of a Salad Plate: Scientific American

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Researchers Create an Electromagnetic "Black Hole" the Size of a Salad Plate

A collection of metamaterial rings efficiently absorbs microwave radiation the way black holes gobble up matter and light, and an optical-light analogue may not be far behind

By John Matson | |October 20, 2009 | | 24

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harnessed metamaterials to create "superlenses" as well as for so-called invisibility cloaking, in which light is bent around an object as if it were not there.

The laboratory black hole is based on a similar approach—establishing a graded index of refraction to bend electromagnetic radiation inward to the cylinder's core. The core, in turn, is an efficient absorber of electromagnetic radiation. In one possible application, the core would be replaced with a "payload" such as a solar cell, with the outer layers funneling light inward. But Cui cautions that such an implementation is a long way off, requiring both that the device be modified to work at visible wavelengths and that the two-dimensional ring be extended to three dimensions.

Cheng and Cui's work represents the preliminary realization of a theoretical proposal put forth just this year by Evgenii Narimanov and Alex Kildishev of Purdue University for a metamaterial structure that could absorb incident light from all directions.

Narimanov, a professor of electrical and computer engineering, says that in the wake of his work with Kildishev, as well as the many studies into extreme light manipulation with metamaterials, he is not surprised to see the theoretical made real. "It's impressive, though, how quickly they have done it," he says.

John Pendry, a physicist at Imperial College London who was among the first to harness the unusual properties of metamaterials, says the new research "constitutes an entirely novel way of constructing an absorber, but at the same time keeping control of the absorbed radiation."

Nevertheless, Pendry notes, the analogy to black holes is imperfect. "Black holes absorb incident radiation and other objects, but the key point about real black holes is the prediction of Hawking radiation emitted by the black hole," he says, referring to physicist Stephen Hawking's hypothesis that is rooted both in general relativity and quantum mechanics. Were it observed, Hawking radiation would provide critical insight into the complicated boundary of the two theories. "A real black hole powers the radiation through its gravitational energy," Pendry says, "but the device reported in this paper has no internal source of energy and therefore cannot emit Hawking radiation."

Besides, the metamaterial black hole is not as ruthlessly voracious as the gravitational kind. Cui estimates that the demonstration black hole only absorbs 80

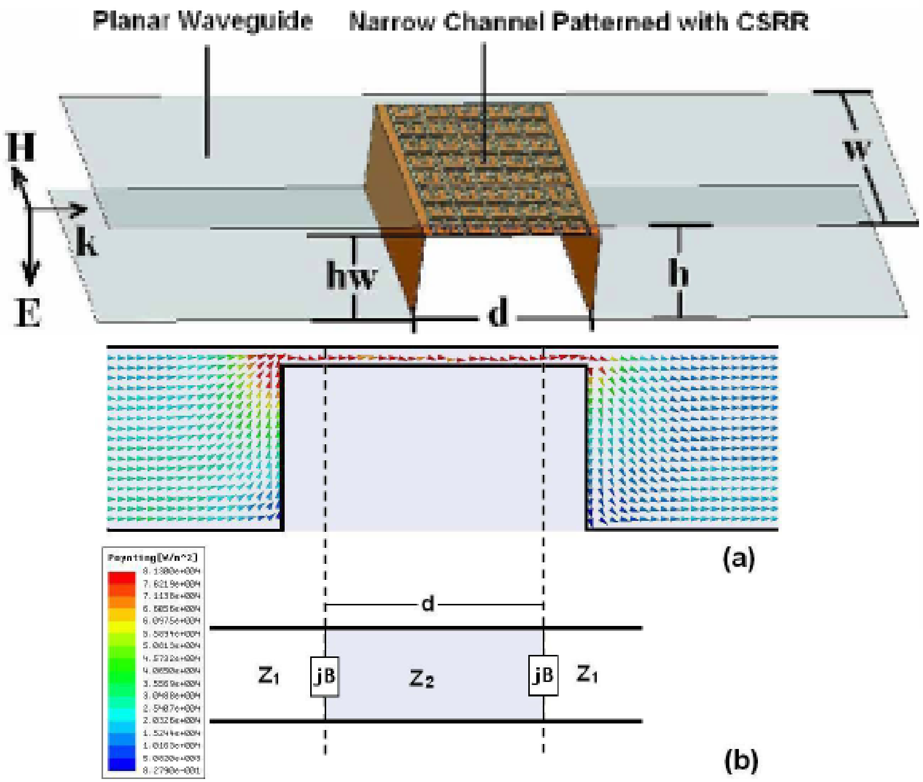
J. B. Pendry

Zero-index medium

PRL **100,** 023903 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

Experimental Demonstration of Electromagnetic Tunneling Through an Epsilon-Near-Zero Metamaterial at Microwave Frequencies

Tunneling Effect of Metamaterial


Planar Waveguide
Narrow Channel Patterned with CSRR
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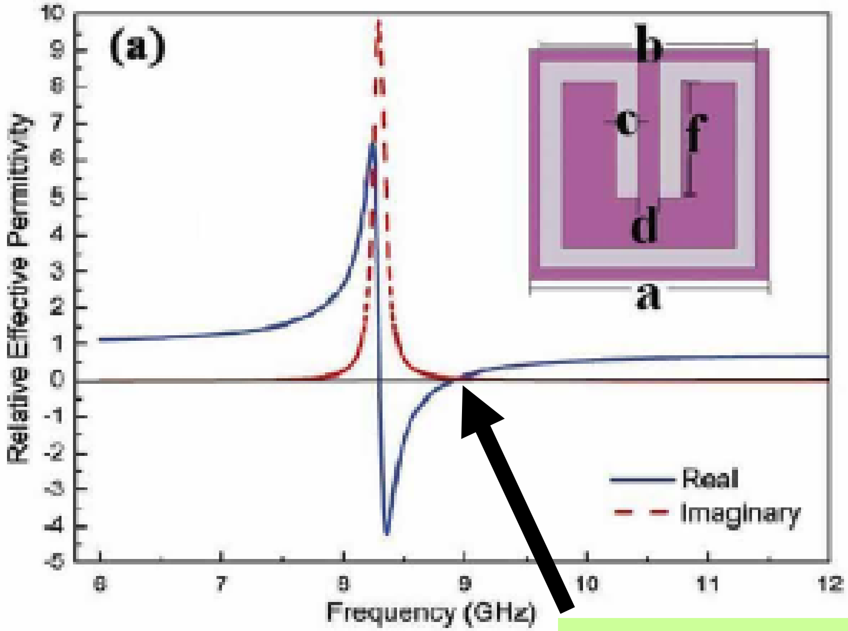
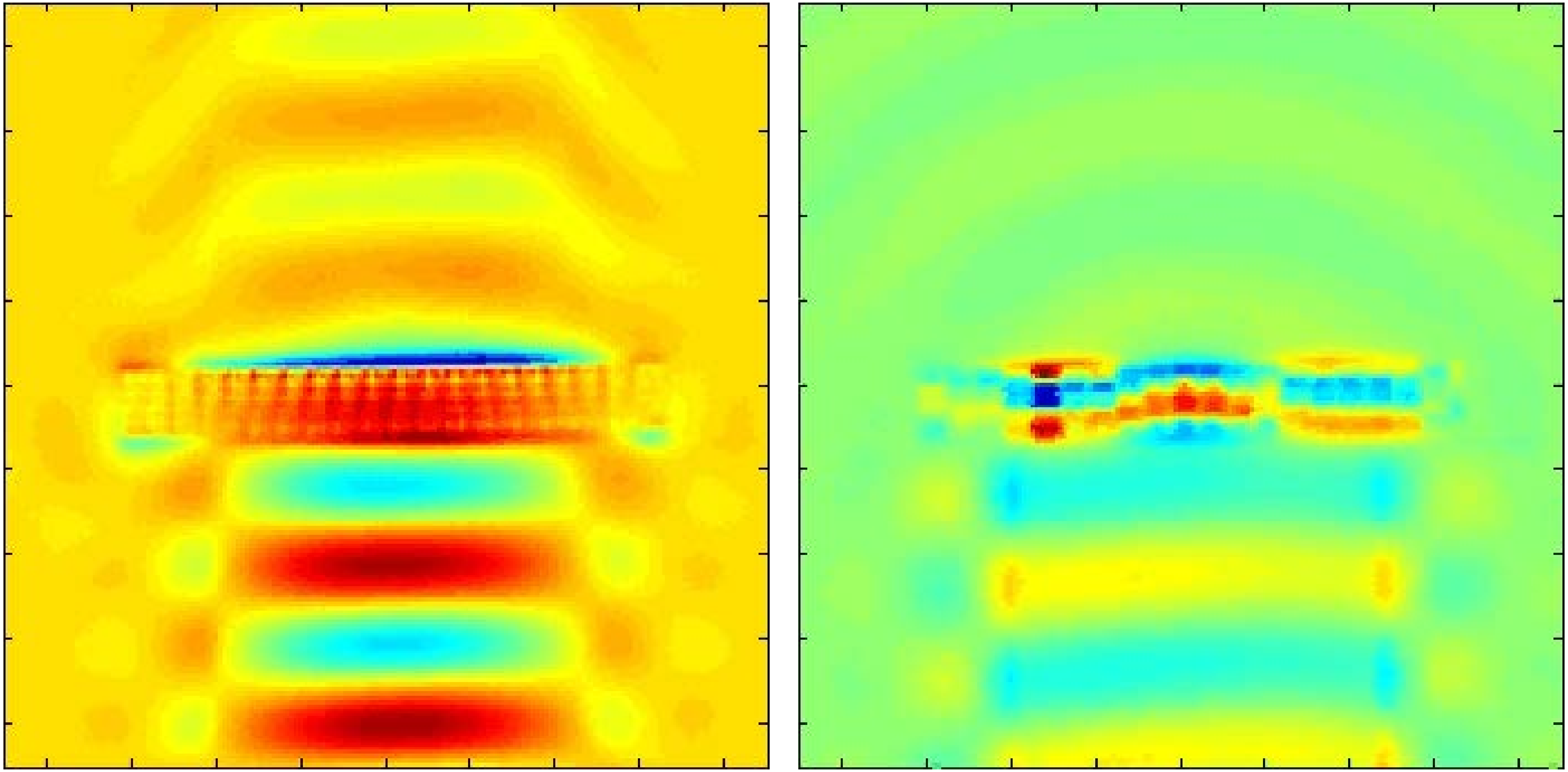


Zero Index

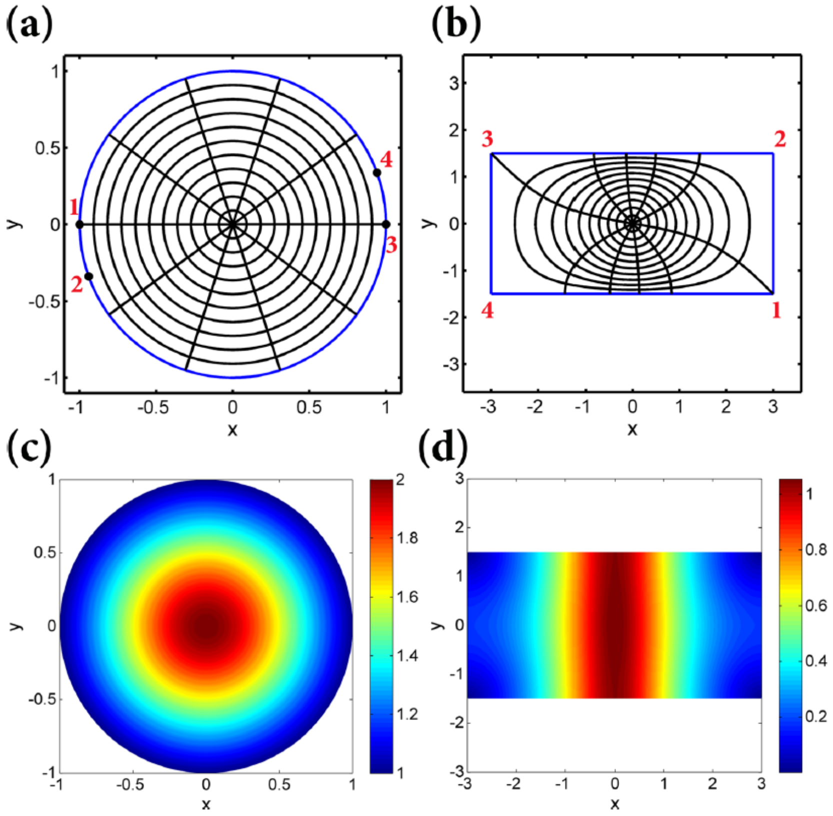
Liu et al., PRL 100, 023903 (2008)

Zero-index medium

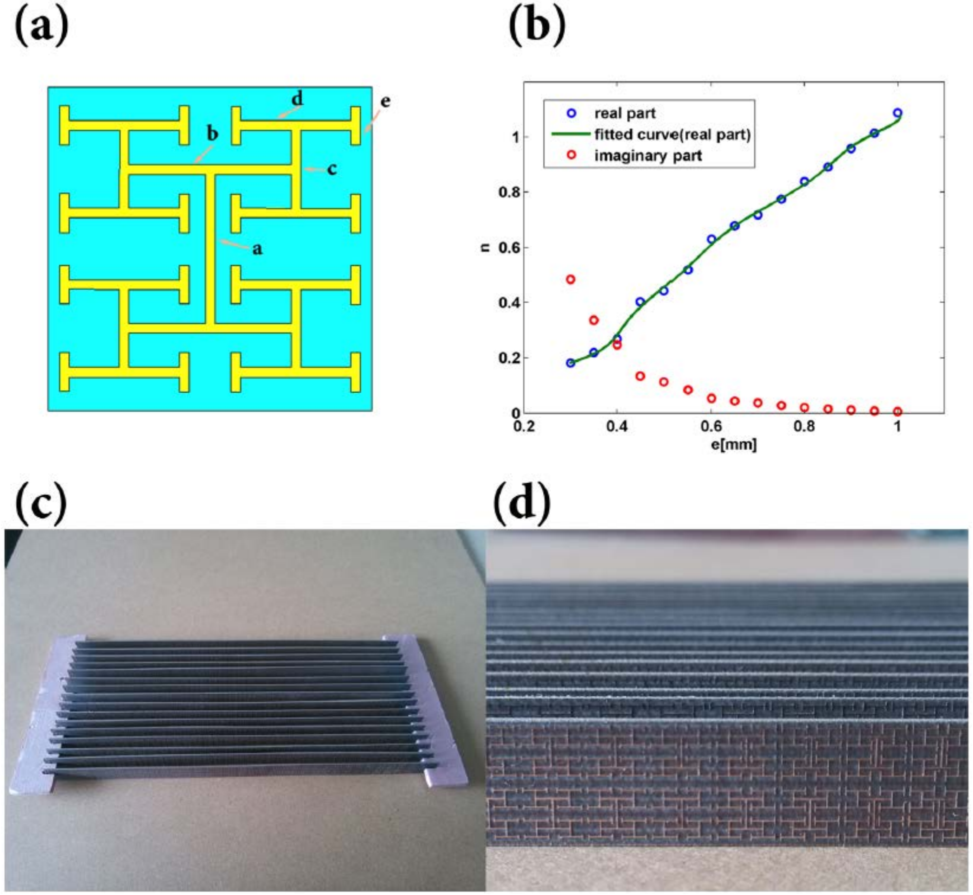


2D Mapper Experiment Result at 8.04GHz: Control Sample

Perfect Relay Lens



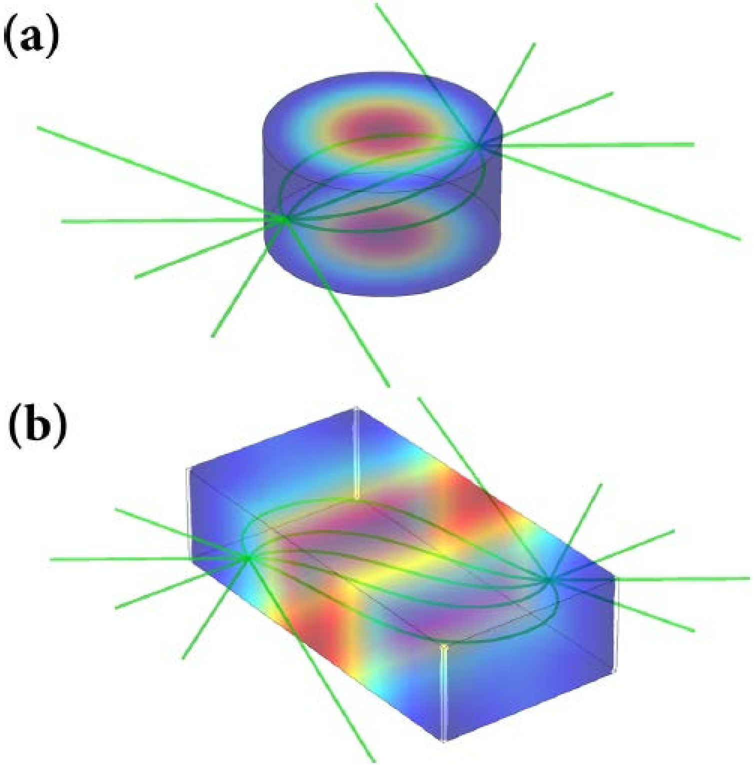
Schwarz-Christoffel mapping



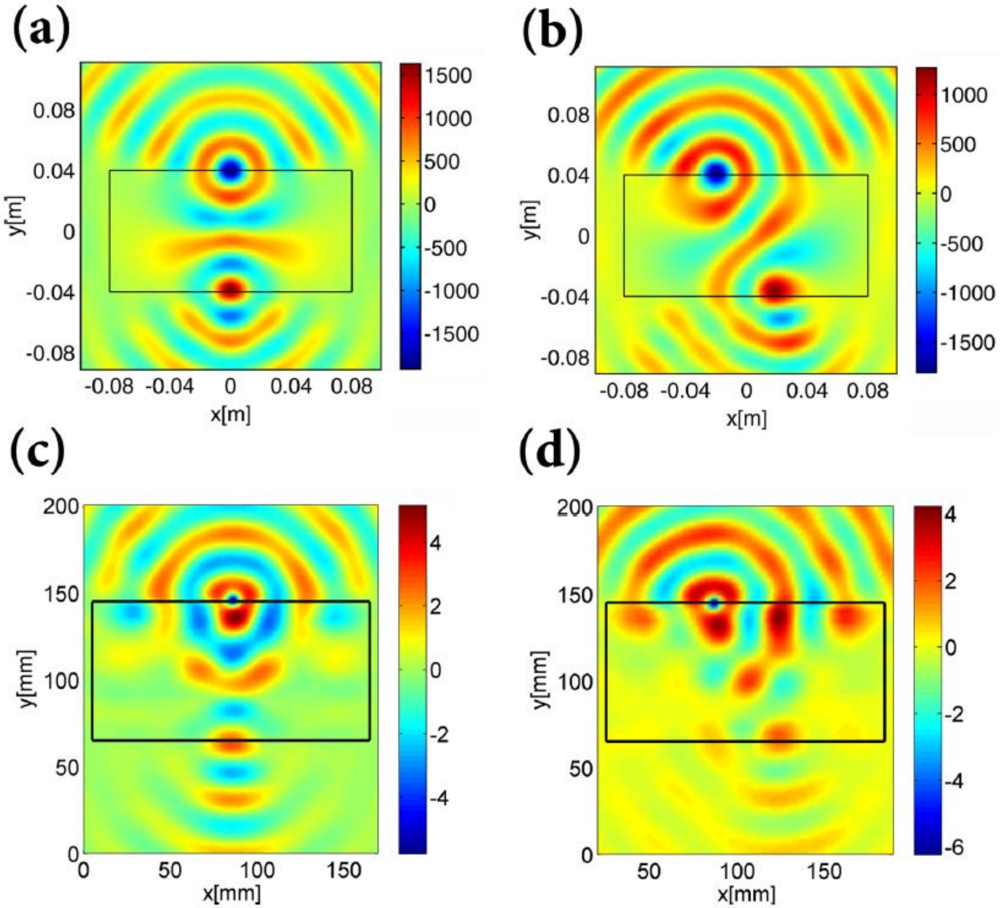
Fabricated sample

Appl. Phys. Lett. 104, 073510, 2014

Perfect Relay Lens

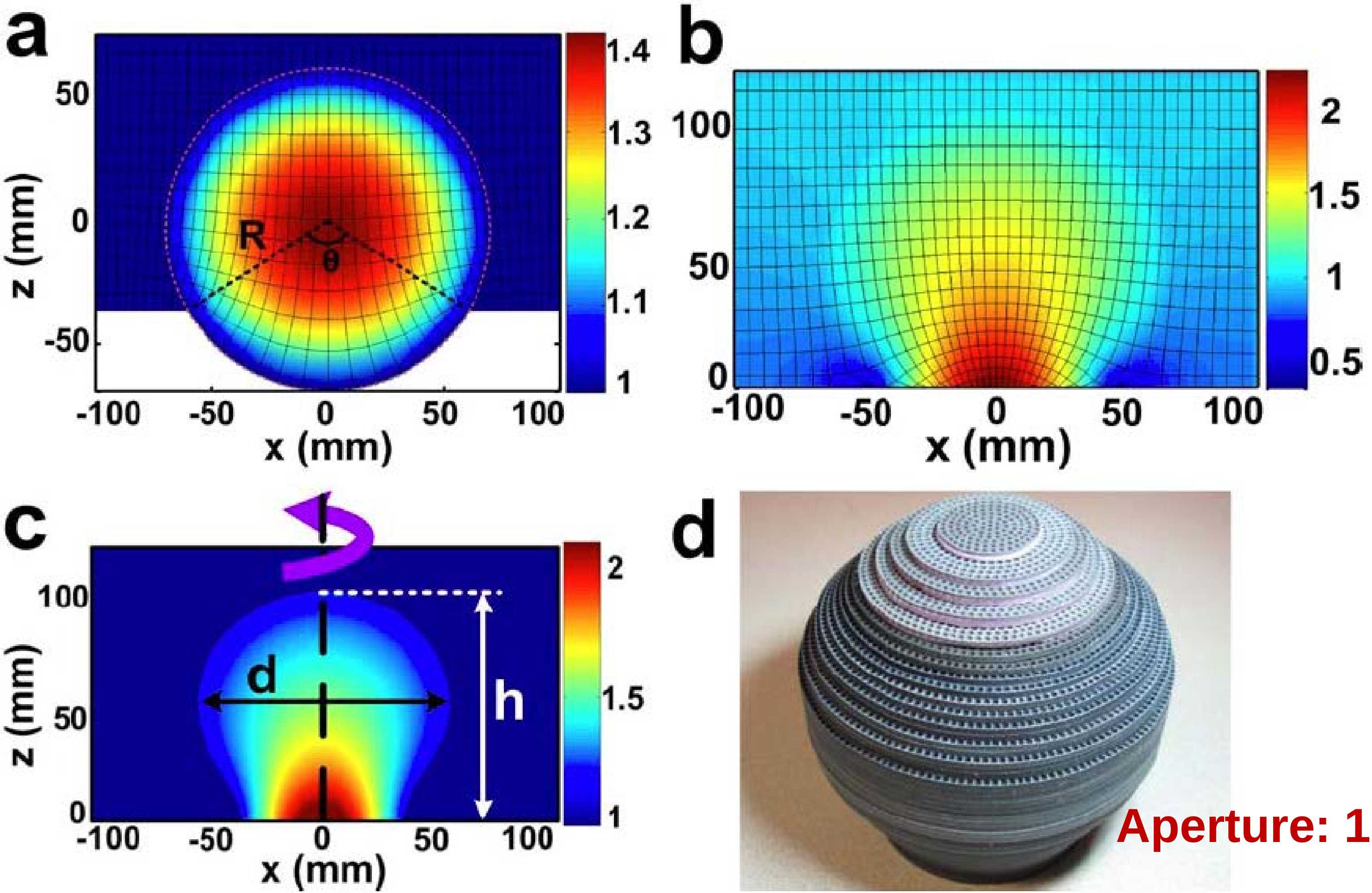


Ray-tracing performance



Simulation and experiment results

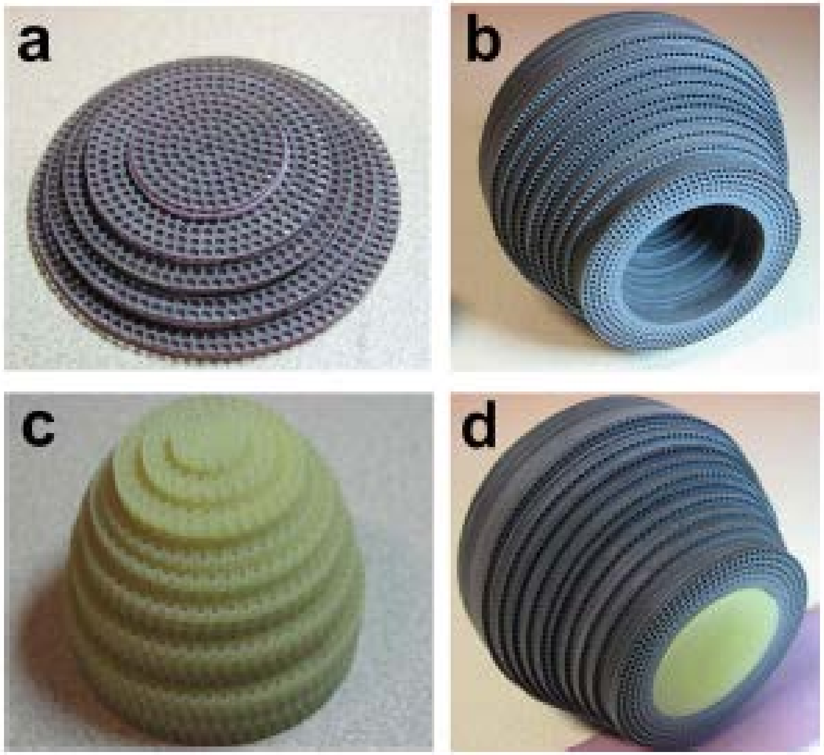
3D Flattened Luneburg Lens



Aperture: 10.8 cm;

Height: 10.4 cm

H. F. Ma and T. J. Cui, Nat. Comm. 1, 124, Nov. 2010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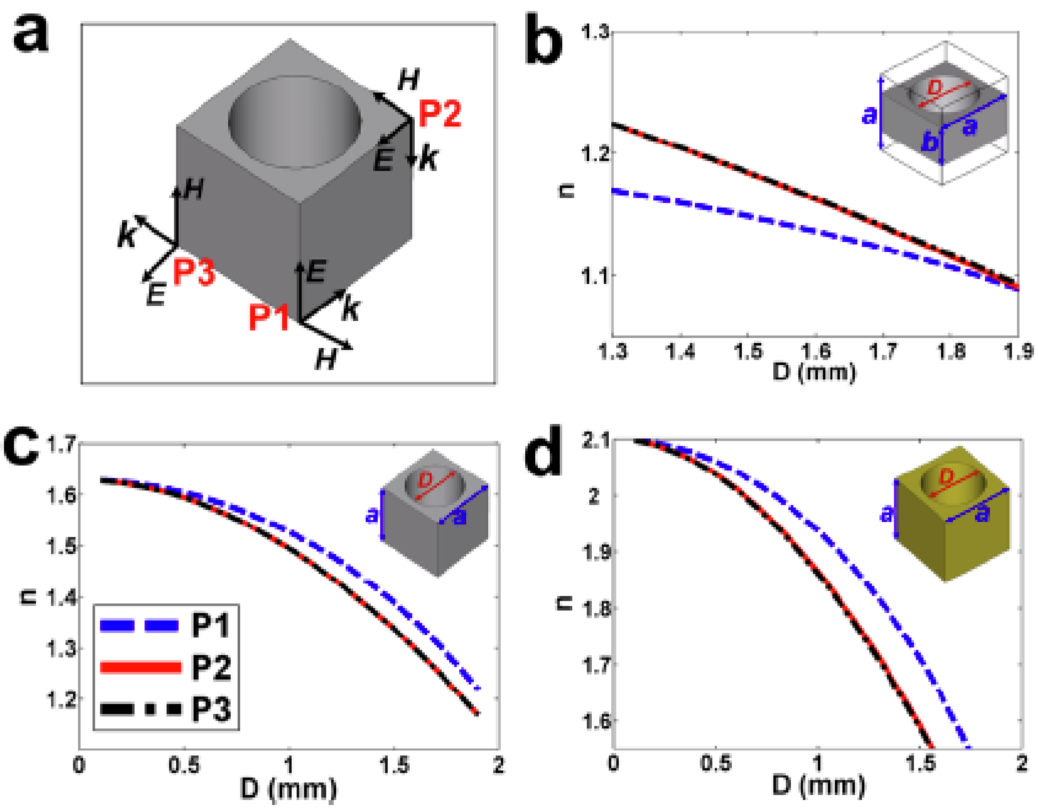
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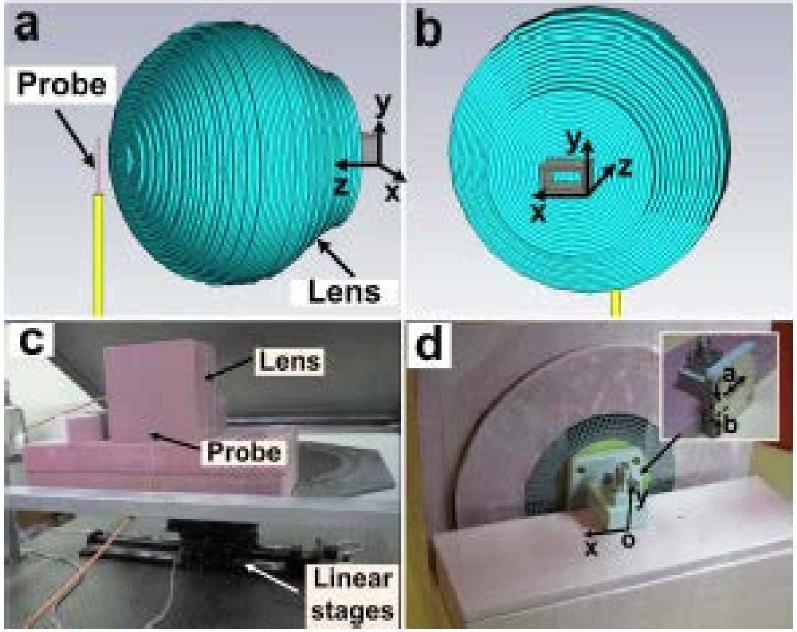
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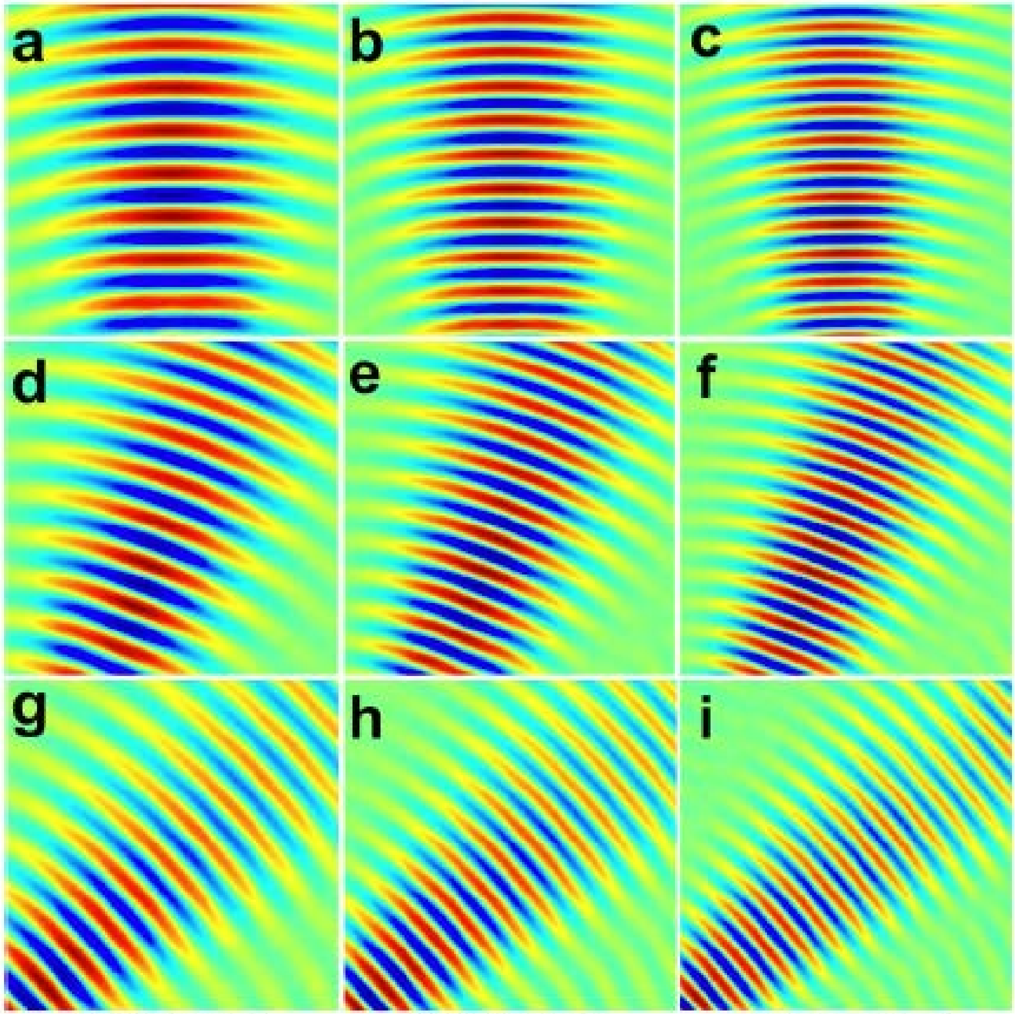
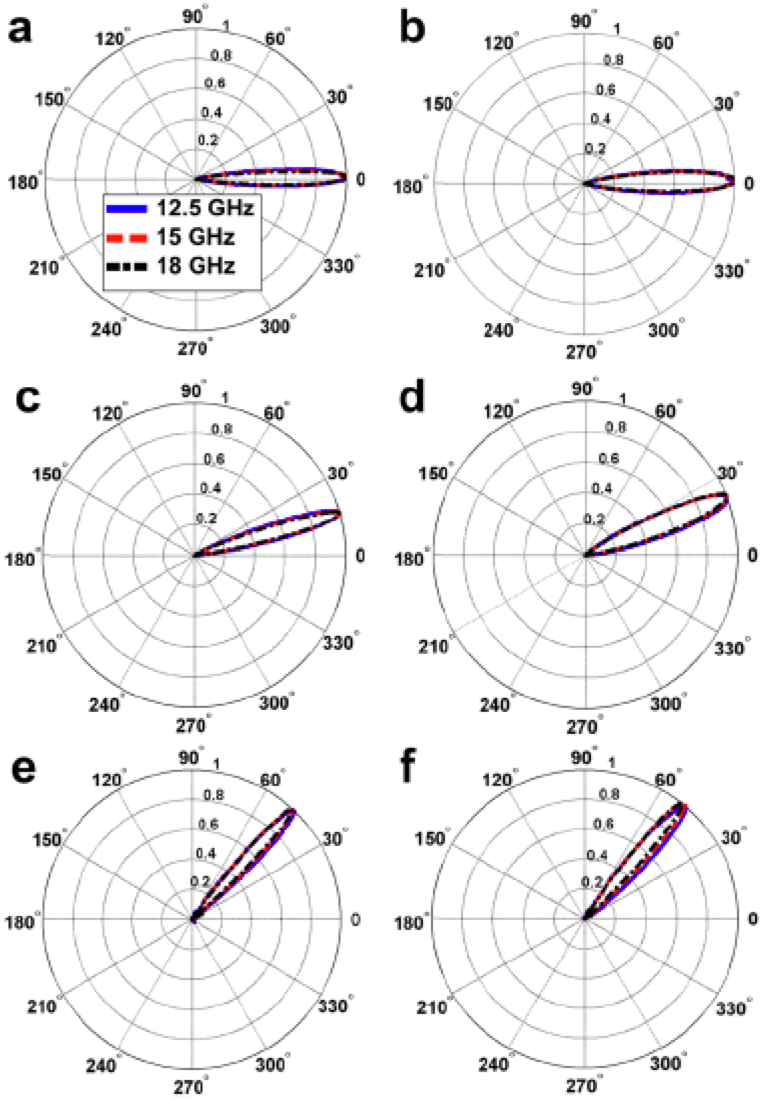
3D Flattened Luneburg Lens



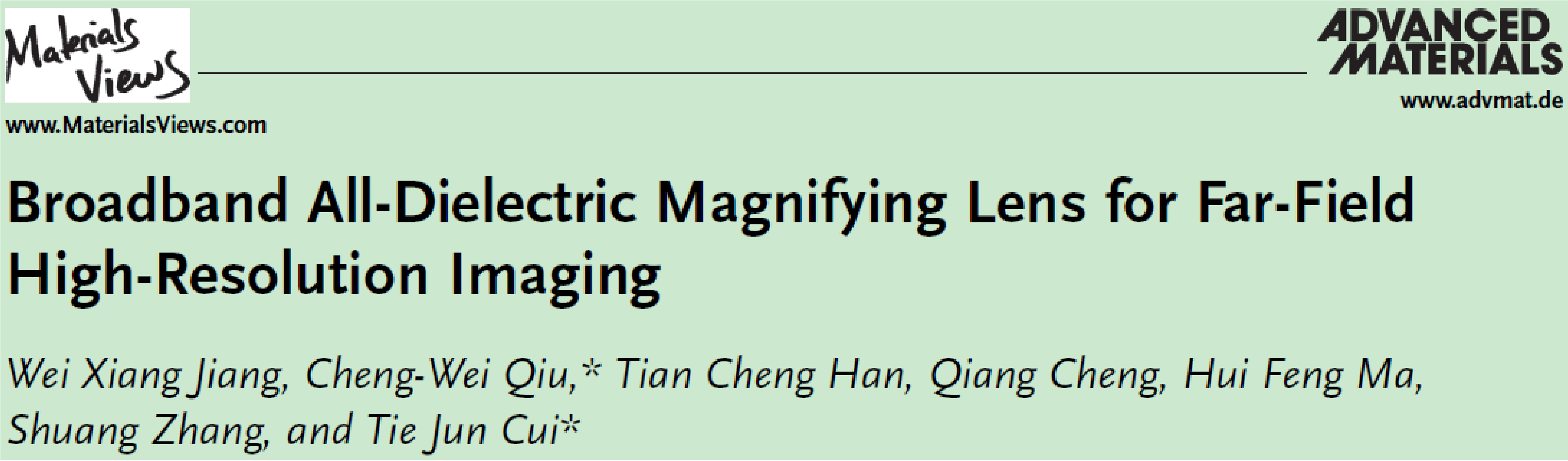
Measured @12.5 GHz

Measured @15 GHz

Measured @18 GHz



High-Resolution Imaging



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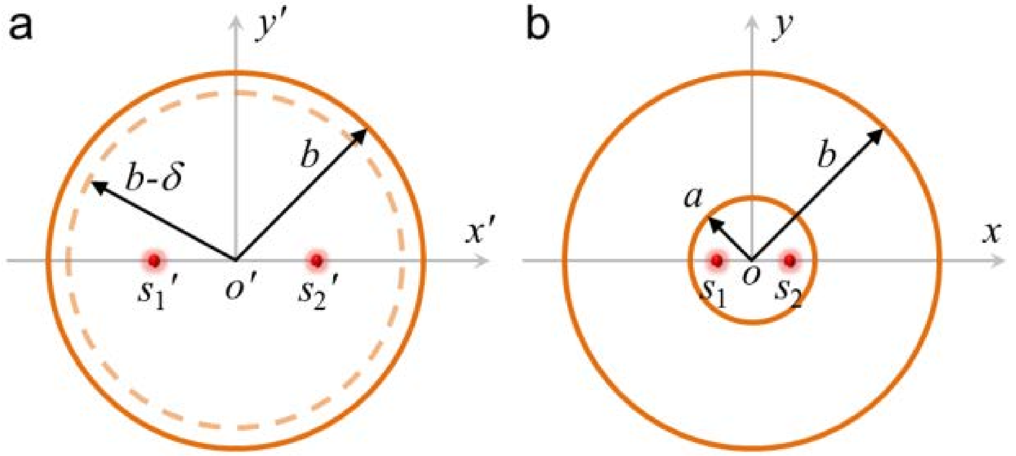
Broadband All-Dielectric Magnifying Lens for Far-Field High-Resolution Imaging

Wei Xiang Jiang, Cheng-Wei Qiu, Tian Cheng Han, Qiang Cheng, Hui Feng Ma, Shuang Zhang, and Tie Jun Cui**

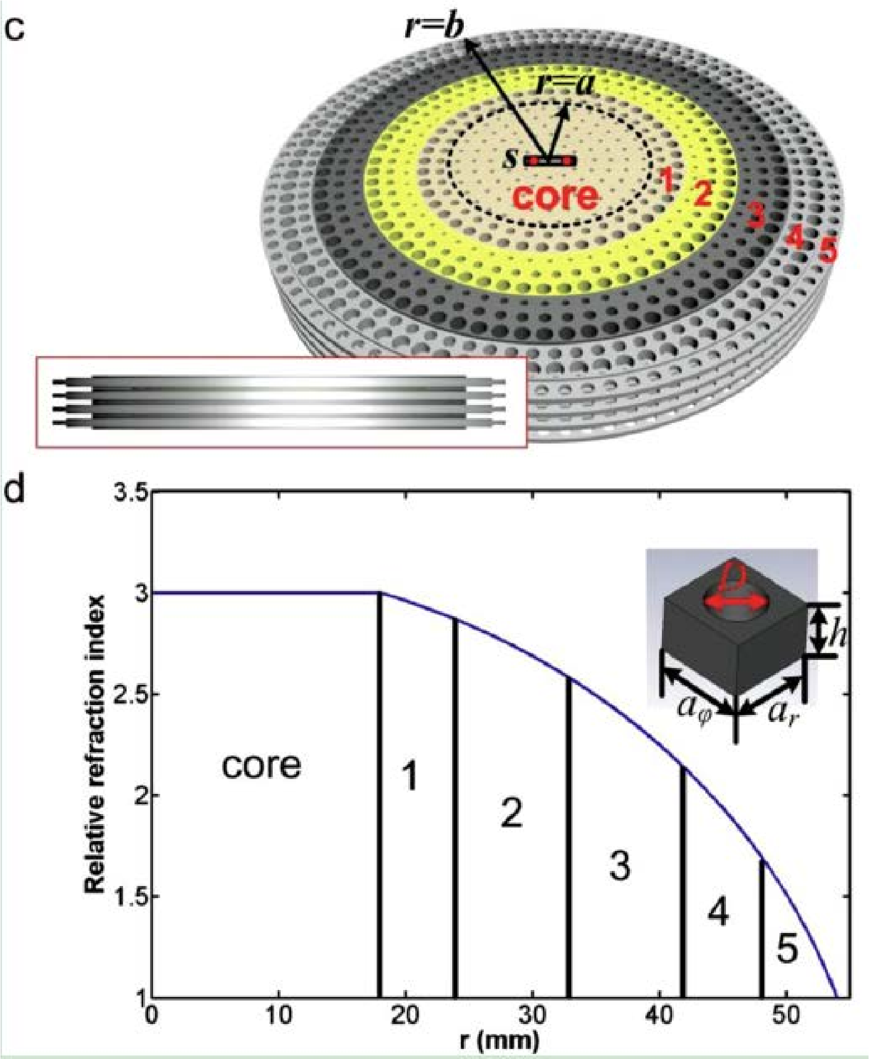


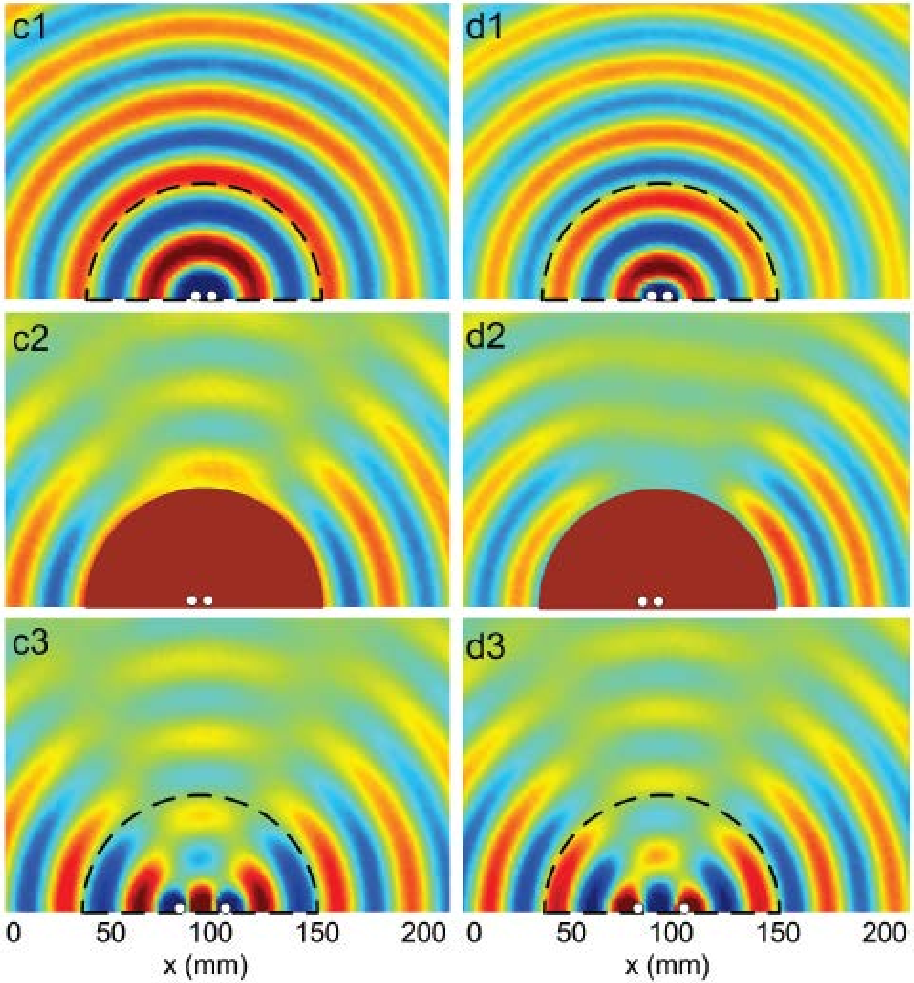
Virtual Space

Real Space

$$n(r) = \begin{cases} b/a & r \le a \\ b/r & a < r \le b. \end{cases}$$

High-Resolution Imaging


c
r=b
r=a
s
core
1
2
3
4
5
d
Relative refraction index
r (mm)
core
1
2
3
4
5
D
h
a_φ
a_r
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50



Measured Results: 9GHz & 10 GHz

Summary

- We proposed some novel devices based on transformation optics, such as, arbitrarily-shaped cloak, non-singular cloak, arbitrarily-shaped concentrator, and so on.
- We produced 3D carpet cloak and 3D flattened Luneburg lens based on inhomogeneous metamaterials.
- We verified the first electromagnetic black hole with the help of metamaterials.
- We also proposed a series of illusion optical devices in microwave band.

Thank you!

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